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ABSTRACT

This report summarizes the latest effort in a series sponsored by the National Science Foundation on the innovation process. It adds to the store of retrospective case studies by documenting historically the significant events in several technological innovations of high social impact. These cases, drawn together by the Battelle Columbus Laboratories, along with previous case studies, illustrate the diverse ways by which research and development activities support each other in the innovation process. The document is an abridged version of a report with more technical details being provided in the complete report entitled "The Interactions of Science and Technology in the Innovative Process: Some Case Studies," available from the National Science Foundation. (Authors/PEB)

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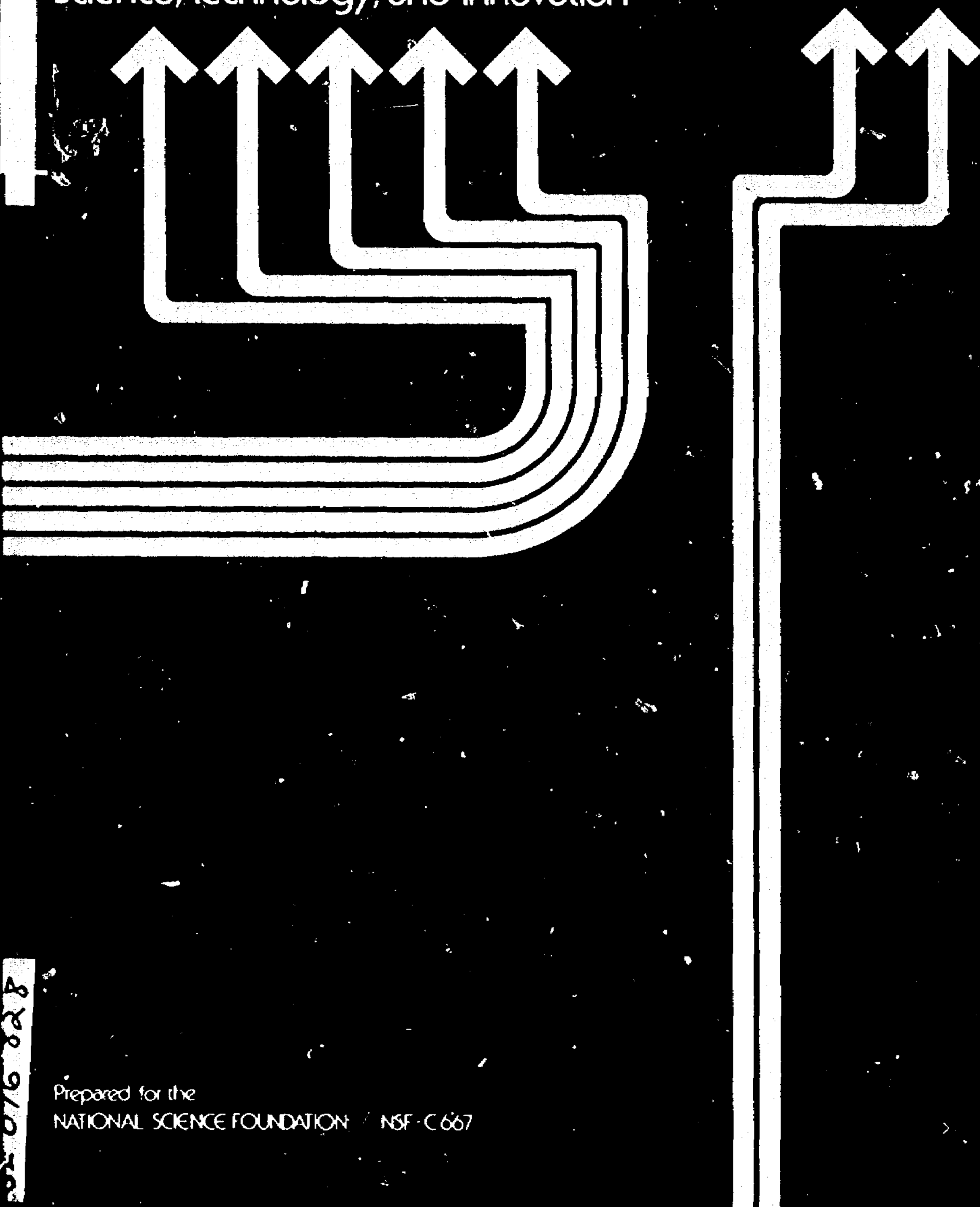

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Foreword

This report summarizes the latest effort in a series sponsored by the National Science Foundation on the innovation process. It adds to the store of retrospective case studies by documenting historically the significant events in several technological innovations of high social impact. These cases, drawn together by the Battelle Columbus Laboratories, along with previous case studies, illustrate the diverse ways by which research and development activities support each other in the innovation process.

This process involves many individuals and institutions responding over time to numerous pressures and motivations. While science and technology play leading roles, the human element and the environment in which innovation takes place are themselves of considerable importance. The Battelle study, taking the broad situation into account, also investigates the role of certain socioeconomic and managerial factors in promoting each of the innovations; and this part of the investigation constitutes a unique contribution to the study of the innovation process.

The findings of this study should prove useful to those interested in the stimulation of technological innovation. To the extent that models emerge, they can provide the basis for planning and policy. New questions about innovation that arise throughout this report reflect the insights gained and should provide possible directions for further studies.

Throughout this study the Battelle Columbus Laboratories team worked closely with the staff in the NSF Division of Science Resources Studies. Drs. Samuel Globe, Charles M. Schwartz, and Girard W. Levy acted as project managers at Battelle. Dr. James J. Zwolenik provided liaison and served as technical advisor to the Battelle team on behalf of NSF.

H. Guyford Stever
Director
National Science Foundation

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Acknowledgments

This document is an abridged version of a report on a study performed at the Battelle Columbus Laboratories under Contract NSF-C 667. The reader who is interested in more technical detail than provided in this abridgment may consult the complete report entitled "The Interactions of Science and Technology in the Innovative Process: Some Case Studies", available from the National Science Foundation.

In addition to the below named authors of this abridged version, the contributors to the project included Duane E. Bell, J. Frank Byrne, Cecil Chilton, Richard D. Falb, W. Halder Fisher, Robert E. Freund, Lemont B. Kier, Edward S. Lipinsky, Garson A. Lutz, Charles S. Peet, William J. Sheppard, Gary S. Stacey, and Ronald A. Williams, all of the Battelle-Columbus Laboratories, and June Z. Fullmer of The Ohio State University.

Acknowledgment is also made of the helpful support given by various members of the staff of the Division of Science Resources Studies at the National Science Foundation. In particular, Dr. James J. Zwolenik took an active interest in our work and provided valuable criticism while performing the usual tasks associated with technical liaison; and Dr. Charles E. Falk encouraged this work from its inception and showed keen interest during its progress. Thanks are also due various referees, unknown to the authors, who, at the request of the National Science Foundation, reviewed and commented on the historical accounts of the study. However, the responsibility for the accounts, for interpretation of events, and for the results of the analysis, rests solely with those staff members of the Battelle Columbus Laboratories who made up the project team.

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Introduction and Overview

Innovation is a term that describes certain activities by which our society improves its productivity, standard of living, and economic status. Basic to the progress of innovation are the tools, discoveries, and techniques of science and technology. In an attempt to understand better how innovation proceeds, and how it is supported by science and technology, we undertook, in the project reported here, an examination of several innovations of high social or economic impact. Our motivation was not only additional knowledge, but also the hope that such knowledge may offer guidelines for generating socially desirable innovations.

Before proceeding to the account of the study, we shall find it useful to define some basic terms, and to consider in greater detail the background and methods of the study. We begin with a discussion of innovation itself.

What Is Innovation?

When inventions or other new scientific or technological ideas are conceived, they do not immediately enter the stream of commercial or industrial application. In fact, many never get beyond the stage of conception, while others are abandoned during the period of development. But some go through a full course of gestation, and finally emerge as new and useful commercial products, processes, or techniques. Such advances are called innovations.

Innovation should be distinguished from scientific discovery, although relevant discoveries may be incorporated into the innovation. Innovation should also be differentiated from invention, although an invention frequently provides the initial concept leading to the innovation. Nor is innovation merely a marginal improvement to an existing product or process. Rather it is a complex series of activities beginning at "first conception", when the original idea is conceived; proceeding through a succession of interwoven steps of research, development, engineering, design, market analysis, management decision making, etc.; and ending at "first realization"*, when an industrially successful "product", which may actually be a thing, a technique, or a process, is accepted in the marketplace. The term "innovation" also describes the process itself, and, when so used, it is synonymous with the phrase "innovative process".

Three Periods Associated With Innovation

As so defined, innovation extends over a bounded interval of time (the innovative period) from first conception to first realization. Implicitly, therefore, we have defined two other periods of time – the "preconception" period, which precedes the time of first conception, and the "post-innovative" period, which follows the time of first realization. During the preconception period science and technology develop the foundation for the innovation. In the post-innovative period improvements of the innovation are made and marketed, and the technology diffuses into other applications. The post-innovative period is sometimes called the period of

*Also termed "culmination" in the historical accounts.

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"technological diffusion", although the two terms are not synonymous, because diffusion is only one of the activities of this period.

Let's look at an example — one of the innovations studied —the Heart Pacemaker. For this innovation, the preconception period saw advances in electricity, especially electrochemistry, in cardiac physiology, and in surgery and intracardiac-therapy techniques. But first conception did not occur until 1928 when Dr. Albert S. Hyman conceived the idea of periodic electrical stimulation of the heart by means of an artificial device, an idea for which he filed a patent application in 1930. The innovative process for the pacemaker proceeded between 1928 and 1960; during this period, batteries were upgraded, the transistor was invented, materials technology enjoyed rapid development, and surgical techniques were advanced. The year 1960 marked the first implantation of a pacemaker in a human patient, and marketing of the device began soon thereafter; 1960 is therefore the date of first realization for this innovation. Since that date — in the post-innovative period — heart pacemakers have become more sophisticated, and work on further improvements continues.

Our study concentrated on the innovative period. But to understand the background from which innovation evolves, and to appreciate the impact of innovation on society, we considered also the preconception and post-innovative periods.

The preconception period presents problems, because it is historically open ended. At what point in history should one start? Electrical stimulation of muscular activity is important to the development of the heart pacemaker. Should one then go back to Galvani's experiments with frogs' legs? Since some time horizon had to be chosen, we selected 1900. The continuity of history makes it difficult to close one's eyes completely to pre-1900 events, so some especially significant scientific and technical events that occurred before 1900 are included in the historical record.

How the Study Was Conducted

We documented the history of five new "cases", jointly selected by the National Science Foundation and the project team. These were analyzed, along with three cases from the project TRACES,* by the methods described below. At the time the new cases were chosen, we expected to find that each case involved a single innovation. Later it became clear that one of the cases — Hybrid Grains and the Green Revolution — included three distinct innovations, so the eight cases represent ten innovations. By reviewing recorded literature and, wherever feasible, by interviewing important participants in the innovative developments, the case investigators documented the history of each innovation.

Throughout this report the term "event" is used in a special and technical sense. The innovative process comprises myriad occurrences, some of which happen sequentially, and some concurrently at different places. From these occurrences, one can identify some that appear to encapsulate the progress of the innovation. These special occurrences are the "events" in the technical sense just referred to.** Their selection reflects the best judgment of the investigators, and is necessarily somewhat arbitrary.

To clarify further how the study proceeded, other terms associated with the "events" are defined below.

A **significant event** is an occurrence judged to encapsulate an important activity in the history of an innovation or its further improvement, as reported in publications, presentations, or references to research. Generally these events follow one another in historical sequence, along channels of developing knowledge. Significant events include other classes of events.

A **decisive event** is an especially important significant event that provides a major and essential impetus to the innovation. It often occurs at the convergence of several streams of activity. In judging an event to be decisive, one should be convinced that, without it, the innovation would not have occurred or would have *been seriously delayed.*

*Technology in Retrospect and Critical Events in Science, a report prepared for the National Science Foundation by the IIT Research Institute, under Contract NSF C535, December 15, 1968.

**This concept was used earlier in TRACES, and was refined in this study.

Since science and technology lie at the focus of the investigation, the great majority of significant events are technical in nature. However, a few events that did not involve science and technology were important enough to be included among the significant events. These events are termed nontechnical.

A **nontechnical event** is a social or political occurrence outside the fields of science and technology. For example, a war or natural disaster would be a nontechnical event, in contrast with a management venture decision within a technical organization, which would be classed as a technical event.

The technical events were then further classified as to where they lie in the spectrum of science and technology. In this spectrum, three regions are defined as follows.

Nonmission-oriented research (NMOR) is research carried on for the purpose of acquiring new knowledge, according to the conceptual structure of the subject or the interests of the scientist, without concern for a mission or application, even though the project within which such research is done may be funded with possible applications in mind.

Mission-oriented research (MOR) is research carried on for the purpose of acquiring new knowledge expected to be useful in some application.

Development is the process of design, improvement, testing, and engineering, in the course of bringing an innovation to fruition.

Each technical event, judged by its predominant purpose or content, was classified as NMOR, MOR, or *development*.

Performing the Analysis

The historical record was subjected to three analyses: (a) an investigation into how certain "factors" affected the decisive events; (b) a search through the historical record for "characteristics" common to the innovations; and (c) a classification in various ways of all significant events.

Decisive Events. The concept of decisive events, their identification in the innovations, and an investigation of the circumstances that affected these events, constituted one of the chief contributions of this study. Twenty-one factors believed to be important to decisive events of the innovative process were identified from the literature on innovation. These factors are social and institutional conditions of the environment in which innovation takes place. A scale of 0, 1, 2, or 3 was established for the factors, designating respectively no, slight, moderate, and high importance to the decisive events. Each of the factors was then rated for each decisive event.

Analysis of the frequency of the ratings for each of the factors provides an assessment of the relative importance of those factors to the decisive events. However, this procedure judges the importance of the factors to the individual decisive events, and not to the innovative process as a whole. Under the circumstances, a high ranking suggests that the factor is important for the innovation as a whole, but a low ranking is ambiguous. In other words, a factor that scores low with respect to the decisive events may yet be important for the innovation as a whole. For example, "Social Factors" was rated as moderately or highly important for only 4 percent of the decisive events. This does not necessarily mean that Social Factors is not important to the process of innovation; what it does mean is that the case investigator, supported by the actual participant in the innovative process whenever he was available, did not judge that Social Factors strongly affected the individual decisive events.

Characteristics of the Case Histories. The second part of the analysis examined the case histories in a qualitative way to determine what "characteristics" appeared frequently in the 10 innovations, each considered as a whole. These characteristics were selected from a review of other studies on innovation.

Of the eight characteristics that emerged most prominently, some, but not all, were similar to certain of the 21 factors. When such similarity exists, and in addition both the factor and the characteristic score high in the analysis, one is justified in ascribing more than average importance to the influence of that condition on the innovative process, and in suggesting a prescriptive judgment. Such is the situation, for example, with respect to the technical entrepreneur. His presence appears to be an important influence that needs to be encouraged if innovation is to be promoted.

Each case history also gives an account of the special conditions and influences that affected the innovation(s) of that case. These accounts, under the title "Implications of the Case", show the need to allow for diversity as well as uniformity in any attempt to provide a general model for innovation.

Significant Events. The last analysis focused on the significant events. To provide further insight into the interaction of science and technology in the innovative process, we examined the frequency of occurrence of NMOR, MOR, and development events; the time of occurrence of each type of event (preconception, innovative, or post-innovative period); and the cumulative increase in each type of event in the years prior to the end of the innovative period.

How the Cases Were Selected

At the outset, five cases for study were selected jointly by the project team and the National Science Foundation. These were new cases, in that the concept of significant events had never been applied to them. The criteria for selection were first, that the innovations should be of high social impact, and second, that the cases should represent diverse fields of technology and application. Thus, one case is from the social sciences, one from agricultural science, one has impact mainly in medical technology, one is highly significant to problems of the environment, and one has its background mainly in physical science.

In addition to documenting the five new cases, we used the results of three cases studied in the earlier project TRACES. For these cases we identified the decisive events, and subjected them, and the history of the innovations, to the same analysis and inspection applied to the five new cases. Reliable identification of the decisive events required some further historical research. The three cases taken from the TRACES project were Oral Contraceptives, Magnetic Ferrites, and Video Tape Recorder.

The following thumbnail sketches describe the eight cases studied.

- *THE HEART PACEMAKER*
  The heart pacemaker is a device that periodically supplies to the diseased human heart an electrical impulse to start each heart beat cycle. In its societal impact, the heart pacemaker epitomizes the problem of artificial organs and organ implants, and foreshadows the ethical questions surrounding the use of such devices. It has unquestionably demonstrated its ability to prolong life. Although the pacemaker is essentially a medical device, contributing technology came from the fields of electricity, electronics, chemistry, and physiology.

- *HYBRID GRAINS AND THE GREEN REVOLUTION*
  The development of hybrid grains is one part of what is sometimes termed the "green revolution", referring to the striking increase in production of cereal grains in many parts of the world. In the study of hybrid grains, hybrid corn was emphasized because it has been a model for hybridization of other grains. Details of the hybridization of the small grains, wheat and sorghum, are included in the study, as is the development of the new varieties of wheat. Improvements in rice are also a part of the green revolution, but its technology involves no novelty beyond that of the other cereal grains, so it was not included in the account. The social impact of improved grains is worldwide, particularly in the recent conversion of some developing countries from grain-deficient to grain-surplus conditions, and in the grain surpluses of the United States. Because agricultural research is itself interdisciplinary, here one does not see the unplanned confluence of technology, as in most of the other cases.

- *ELECTROPHOTOGRAPHY*
  Electrophotography is the process of duplicating or copying visual material by the application of electrostatics and photoconductivity. The best known application of electrophotography is the office

copier. Electrophotography has already revolutionized business-office procedures, and is producing further effects on the world of duplicating, publishing, and information processing. Important contributing technology came from electrostatics, photoconductivity, and corona emission.

- *INPUT-OUTPUT ECONOMIC ANALYSIS*
  Input-output economic analysis is a tool for examining the structure of an economy by recording the details of interindustry commerce within that economy. It has found wide application in related areas such as studies of economic development, predictions of economic needs, and other aspects of national and group economics. Background technology came from general economic modeling and statistical analysis. Contributing technology came from the field of machine computation, especially the electronic digital computer.

- *ORGANOPHOSPHORUS INSECTICIDES*
  Organophosphorus insecticides are an extremely diverse group of toxic agents. Their properties range from short residual action to long persistence, from broad-spectrum insecticidal activity to high selectivity combined with low mammalian toxicity. Some, applied to the plant system by absorption as systemic insecticides, produce their effect as the target pests attack the plant. Because they need not be broadcast through large portions of the biosphere and are more selective in their effects, these products are less likely to affect life forms that are not part of the target population. They are an example of pest-control schemes intended to be more ecologically desirable than widely broadcast chlorinated hydrocarbons such as DDT or chlordane. This is an interesting case because its diverse technological roots, including organic chemistry, toxicology, and nerve physiology, came together through the deliberate formation of an interdisciplinary team, rather than from unplanned circumstance.

- *ORAL CONTRACEPTIVES**
  Oral contraceptives provide a hormonal approach to contraception. The hormones in the contraceptive pill suppress ovulation, and thereby prevent conception. Oral contraceptives are inexpensive and have been widely accepted. The principal supportive technologies are steroid chemistry, hormone research, and reproductive physiology.

- *MAGNETIC FERRITES**
  Magnetic materials are widely used in contemporary technology. Of special importance among such materials are the magnetic ferrites, which, because they are ceramics, often have advantages over metallic magnetic materials. They combine the inherently high electrical resistance of ceramics with the magnetic properties of certain metals. Magnetic ferrites are used widely in communications, microwave, and computer equipment. The technological roots of this case are found in magnetic theory, communications science, materials science, and crystal chemistry.

- *VIDEO TAPE RECORDER**
  The video tape recorder is a device that extends the technique for magnetic recording of electrical signals to the frequency range required for television broadcasting. It permits wide flexibility in editing and scheduling of television broadcasts. In fact it has revolutionized the television broadcast industry and has found applications as well in education, training, and other fields. Electromagnetic and communications theory, electronics, the technology of audio recording, and servomechanism design provided the foundations for this case.

*This case was taken from the TRACES project.

Analysis and Conclusions

This section presents some details of the analyses that were explained briefly in the Introduction and Overview, and summarizes the conclusions drawn from these analyses.

The 21 Factors and the Decisive Events

As explained earlier, 21 factors of probable importance to the direction and rate of the innovative process were selected from the general literature. These factors were rated as to degree of importance to each of the decisive events of the 10 innovations. The factors are defined or illustrated briefly below.

The first three factors are related to various motivational influences:

Recognition of Scientific Opportunity – motivation for the timely acquisition of new fundamental knowledge.

Recognition of Technical Opportunity – motivation for the timely improvement of an existing product or process.

Recognition of the Need – motivation for solving the problem or meeting the need satisfied by the eventual innovation.

The next four factors involve actions taken consciously by management:

Management Venture Decision – decision by an organization to invest in some large-scale technical activity. The activity need not be directly related to the innovation under study. The decision is usually followed by the formation of an R&D team to carry out the activity.

Availability of Funding – the existence (rather than the extent) of financial support. Early in the innovative process, even limited funds can provide for critical experiments that may influence management decisions.

Internal R&D Management – role of supervisors and other management personnel within the performing organization. It includes those who give specific suggestions and directions to R&D personnel, set goals and schedules, and assign staff.

Formal Market Analysis – economic feasibility studies of an innovation, especially estimates of its potential market.

The next four factors may involve management in some sense, but do not necessarily imply specific action by management:

Prior Demonstration of Technical Feasibility – earlier activities that established the practicability of further development or the utility of further research.

Technological Gatekeeper – an individual who identifies scientific or technical information of relevance to the interests and activities of the researchers.

Technical Entrepreneur – an individual within the performing organization who champions a scientific or technical activity; he is sometimes also called a "product champion".

Patent/License Considerations – existence of patent protection of inventions, or of licensing arrangements.

The next four factors describe peer-group forces that impinge on the R&D scientist:

Technology Interest Group – (also known as the "invisible college") a group of researchers from different institutions who exchange ideas and findings via personal meetings, letters, etc., as distinct from the formal (publication) channels of communication.

In-House Colleagues – technical personnel within the performing institution who collaborate on or otherwise facilitate the activity. Often they are members of an R&D team.

External Direction of R&D Personnel – suggestion of goals and approaches by persons outside the performing organization.

Competitive Pressures – competition among persons and organizations working in the same technical area.

The next two factors are circumstances that are usually unplanned or accidental:

Serendipity – emergence, during the event, of unexpected scientific or technical results that proved useful in promoting the innovation.

Technology Confluence -- merging of major channels of development, often from diverse scientific fields, making possible new advances.

The remaining four factors refer to external factors that form the general environment within which the innovative process takes place:

General Economic Factors – such as a recession or depression.

Social Factors -- such as group customs, beliefs, and attitudes.

Political Factors – such as elections or war.

Health and Environmental Factors – such as famine or disease.

The last four factors permit consideration of influences not included in specific external factors such as, for example, Competitive Pressures. These categories were purposely left broad, so that the appropriate factor could be applied to a given event from among the diverse possibilities.

Conclusions About the Factors

No factor was judged important for every event, and yet each of the factors was of some importance to more than one event. For each factor listed, Table 1 presents, in descending order, the percentage of all decisive events for which that factor was judged moderately or highly important. Further statistical analyses of the factor ratings yielded an order only slightly different from that of Table 1, and do not affect the conclusions listed below:

TABLE 1. PERCENTAGE OF DECISIVE EVENTS RATED MODERATELY OR HIGHLY IMPORTANT FOR EACH FACTOR

Factors	Percentage of Decisive Events
Recognition of Technical Opportunity	87
Recognition of the Need	69
Internal R&D Management	66
Management Venture Decision	62
Availability of Funding	62
Technical Entrepreneur	56
In-house Colleagues	51
Prior Demonstration of Feasibility	49
Patent/License Considerations	47
Recognition of Scientific Opportunity	43
Technology Confluence	36
Technological Gatekeeper	30
Technology Interest Group	29
Competitive Pressures	25
External Direction to R&D Personnel	16
General Economic Factors	16
Health and Environmental Factors	15
Serendipity	12
Formal Market Analysis*	7*
Political Factors	5
Social Factors	4

*In retrospect, one might argue that Formal Market Analysis was bound to be rated low, because such an analysis usually is done only once, and does not continue through the innovative period. But the same argument might apply to Management Venture Decision, which ranks high.

Economic Factors, Health and Environmental Factors, Political Factors, and Social Factors — rank at the bottom. However, this conclusion bears on the effect of the factors on the individual decisive events, and is not applicable to the innovative process as a whole.

Generalizations from the Case Histories

Table 2 lists eight important characteristics frequently observed and reported in previous studies of the innovative process. Each of the ten innovations was examined for these characteristics. In Table 3, which summarizes the results, "X" indicates that the characteristic was important, and "–" that it was not important to the innovation. The eight characteristics were found in most of the ten innovations, although the independent inventor was found in only three. The following conclusions may be drawn:

- The technical entrepreneur, whose importance was highlighted in the study of the "factors" is also a "characteristic" important in nine of the ten innovations. This is the strongest conclusion that emerges from the study. In fact, in three innovations, the technical entrepreneur persisted in the face of the inhibiting effect of an unfavorable market analysis. If any suggestion were to be made as to what should be done to promote innovation, it would be to find if one can [illegible] technical entrepreneurs
- Early recognition of the need appeared in nine of the innovations. This confirms the high rating for the corresponding factor in the analysis of the decisive events, and substantiates the importance attributed to "market pull" in other studies.
- [illegible]
- [illegible]

TABLE 2. SOME PREVIOUSLY REPORTED CHARACTERISTICS OF THE INNOVATIVE PROCESS

1. ***Early Recognition of Need***
   Recognition of the need for the innovation generally occurs prior to the availability of the technological means for satisfying the need.
2. **Independent Inventor**
   The independent inventor, working on his own behalf, is often important in the initiation of the process.
3. **Technical Entrepreneur**
   The technical entrepreneur is often important to the successful culmination of the innovation.
4. **External Invention**
   Many innovations arise from inventions which originate outside the organization that developed the innovation.
5. **Government Financing**
   Government financing is important in many innovations.
6. **Informal Transfer of Knowledge**
   Innovations are facilitated by informal transfer of knowledge, much more than through formal channels of communication.
7. **Supporting Inventions**
   Innovations generally require additional supporting inventions beyond the initiating invention.
8. **Unplanned Confluence of Technology**
   The innovative process is frequently facilitated by an unplanned confluence of technology.

technology is especially interesting. Table 3 shows that an unplanned confluence of technology was important to six of the innovations. But confluence of technology was present for the other four innovations as well, although it came about from deliberate planning, rather than accident. For the three innovations of improved grains, technology confluence occurred because agricultural science is itself an interdisciplinary field, and has long been supported on that basis. The remaining innovation, Organophosphorus Insecticides, made use of a deliberately formed interdisciplinary team. Technology Confluence [illegible] ranks near the middle (Table 1) [illegible] The lesson to be learned here is that [illegible] should not be left to accident but should be promoted through [illegible]

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TABLE 3. CHARACTERISTICS OF THE INNOVATIVE PROCESS

Indicated as important (X) or unimportant (–) for each innovation

Innovation \ Characteristic	Early Recognition of Need	Independent Inventor	Technical Entrepreneur	External Invention	Government Financing	Informal Transfer of Knowledge	Supporting Inventions	Unplanned Confluence of Technology
Heart Pacemaker	X	X	X	X	– X	X	X	–
Hybrid Corn	–	–	X	X	X	X	X	–
Hybrid Small Grains	X	–	-	X	X	X	X	–
Green Revolution Wheat	X	–	X	–	X	X	X	X
Electrophotography	X	X	X	X	–(a)	X	X	X
Input Output Economic Analysis	X	X	X	X	X	X	X	X
Organophosphorus Insecticides	X	–	X	X(b)	X	X	X	–
Oral Contraceptives	X	–	X	X	–	X	X	X
Magnetic Ferrites	X	–	X	–	X	X	X	X
Video Tape Recorder	X	–	X	X	–	–	X	X

(a) But limited Government funds were provided to a related development, giving indirect aid.

(b) "External Invention" occurred only because World War II enabled American Cyanamid to market the innovation in advance of I. G. Farben.

Analysis and Classification of the Significant Events

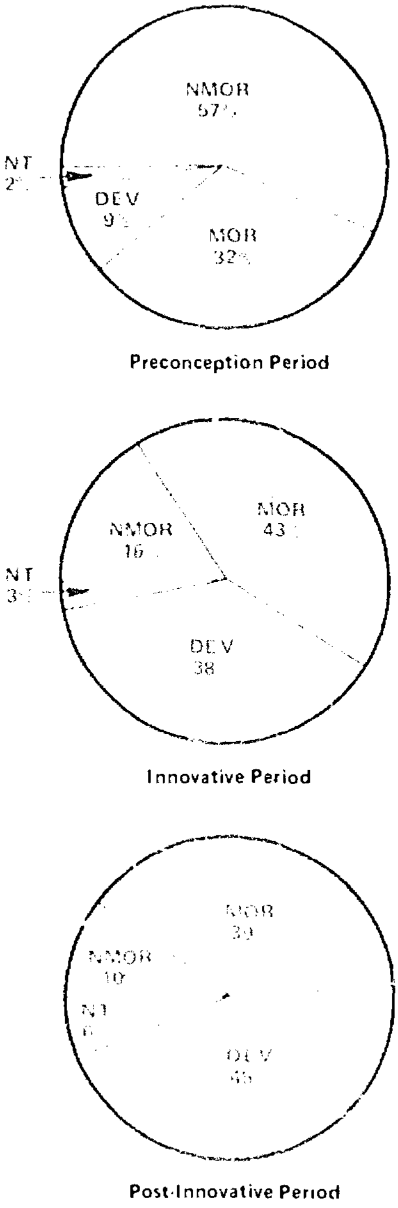
To gain further insight into the roles of science and technology in the innovative process, we examined the 533 significant events of the 10 innovations studied. These significant events were classified as to type – nonmission-oriented research (NMOR), mission-oriented research (MOR), development, and nontechnical events. Of the events, 34 percent were classified as NMOR, 38 percent were MOR, 26 percent were development, and 3 percent were nontechnical.

Additional understanding about the innovative process as a whole was obtained by considering its duration. Table 4 presents the dates of initial conception and first realization for each of the ten innovations studied. For some of the innovations, the time from conception to realization was very short, as in the case of the Video Tape Recorder, which was developed within six years from its initial conception. Other innovations covered a much longer time span. From the small sample of innovations studied, there is no evidence that the time period from conception to realization is becoming shorter. In fact, two of the more recent innovations (Input-Output Economic Analysis and the Heart Pacemaker) involve the longest time spans. The average for the ten innovations studied was 19 years.

An explanation of the striking difference between the longest duration and the shortest gives some insight into the variety of circumstances surrounding innovations. The development of the Heart Pacemaker, which was 32 years in the process, faced a number of inhibiting influences, including social taboos, active opposition within the medical profession and outside it, and the occurrence of World War II. Yet its most serious obstacle was probably the absence of necessary technology, as in

TABLE 4. DURATION OF THE INNOVATIVE PROCESS FOR TEN INNOVATIONS

Innovation	Year of First Conception	Year of First Realization	Duration, years
Heart Pacemaker	1928	1960	32
Hybrid Corn	1908	1933	25
Hybrid Small Grains	1937	1956	19
Green Revolution Wheat	1950	1966	16
Electrophotography	1937	1959	22
Input Output Economic Analysis	1936	1964	28
Organophosphorus Insecticides	1934	1947	13
Oral Contraceptive	1951	1960	9
Magnetic Ferrites	1933	1955	22
Video Tape Recorder	1950	1956	6
Average Duration			19.2



NMOR: Nonmission-Oriented Research
MOR: Mission-Oriented Research
DEV: Development
NT: Nontechnical

FIGURE 1. DISTRIBUTION OF SIGNIFICANT EVENTS IN THE PRECONCEPTION, INNOVATIVE, AND POST-INNOVATIVE PERIODS

electronics and materials. On the other hand the Video Tape Recorder required only existing technology, and so proceeded from first conception to first realization in six years.

Figure 1 presents the proportion of significant events occurring during each of the three periods making up the historical sequence.

In the preconception period, over half of the events were NMOR, and an additional one-third were MOR. Thus, nearly ninety percent of the precursor events consisted of fundamental and applied scientific research.

In the innovative period, 16 percent of the events were NMOR, 43 percent were MOR, and 38 percent were development. NMOR events continue to occur in the innovative period and even beyond; but overcoming technical barriers becomes more and more important as innovation proceeds, so that a higher percentage of MOR and development events occur in this period than in the preconception period.

In the post-innovative period, when diffusion and improvement occur, 10 percent of the events identified were NMOR, 39 percent were MOR, and 45 percent were development.

The differences in the rates of accumulation of NMOR, MOR, and development events are further highlighted in Figure 2. The events for each innovation have been related in time to the date of first realization of the innovation, and combined and plotted in terms of the number of years prior to that date. The figure indicates that half of the NMOR events occurred 30 years before first realization. Thus, the innovations made use of published fundamental research which had been available for some time prior to the innovative period. Approximately

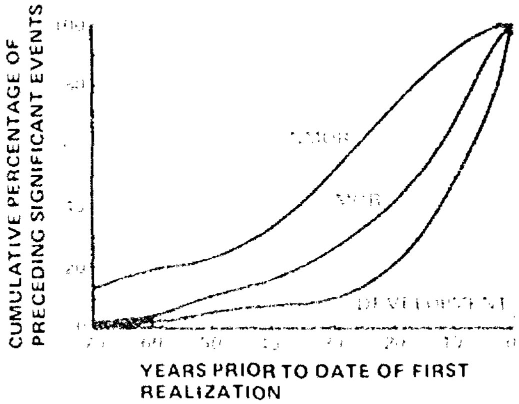


FIGURE 2. CUMULATIVE INCREASE IN TYPES OF SIGNIFICANT EVENTS

half of the MOR events occurred in the last 15 years, and approximately half of the developmental activity occurred in the last 10 years, *preceding first realization.*

In summary of the analysis and classification of the significant events, we may draw the following conclusions:

- The time span from first conception to first realization is not growing shorter, as far as can be judged from our limited sample, and in contrast to widely held ideas. This time span averages about 19 years and ranges from 6 to 32 years for the ten innovations studied. The difference in duration between the longest and the shortest is caused mainly by a difference in availability of technology for the two innovations.
- In the preconception and innovative periods, MOR and development events become more dominant as time progresses, although NMOR events are found up to and beyond the date of first realization. Such late NMOR events usually represent a process of feedback and diffusion from technology to science.

Can Innovation Be Managed?

Consideration of the conclusions reached from analysis of the decisive events, from the characteristics of the case histories, and from the classification of the significant events, leads one to some conjectures about managing innovation.

There has always been argument about the extent to which research and development can be managed. Whatever may be the merits of differing positions in this argument, we may confidently assert that, in the spectrum of science and technology, NMOR is the most difficult to manage, if it can be managed at all. Furthermore, as we have seen, significant NMOR events continue to occur up to the end of the innovative process; h·ce, we are forced to conclude that innovation cannot be completely controlled or programmed. Also, the actions of the technical entrepreneur, or the role of such motivational forces as recognition of need and recognition of technical opportunity, involve inventive or creative activities that do not lend themselves to detailed planning. Hence the high ranking of these factors in the analysis supports further the conclusion that innovation cannot be fully planned. We are therefore led to recommend that management, in trying to promote innovation, permit and encourage the opportunity to act upon ideas that fall outside the established or recognized pattern.

But if innovation cannot be fully controlled, we nevertheless can discern ways in which management can help it along. Our analysis reveals two such ways by demonstrating the importance of funding and of the confluence of technology. As to funding, it need not be munificent, at least in the early stages. It not only permits R&D to proceed, but probably also aids the innovative process by the confidence management generates in the R&D team through financial support. As to confluence of technology, it seems almost essential to innovation. Yet it too often occurs without planning, and one suspects that here is an opportunity for management, by promoting interdisciplinary R&D teams, to accelerate the innovative process.

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Historical Accounts of the Cases

This section contains an abbreviated account of each of the cases studied. The historical records, summarized in this account constitute the information base from which the analyses derived. The 89 decisive events, selected from among the significant events in the historical accounts, are described briefly, and the features that appear most important to the culmination of the innovative process are highlighted. Charts illustrate the flow of scientific and technical information within the various channels of development, for each case. On these charts, the time scale is schematic only.

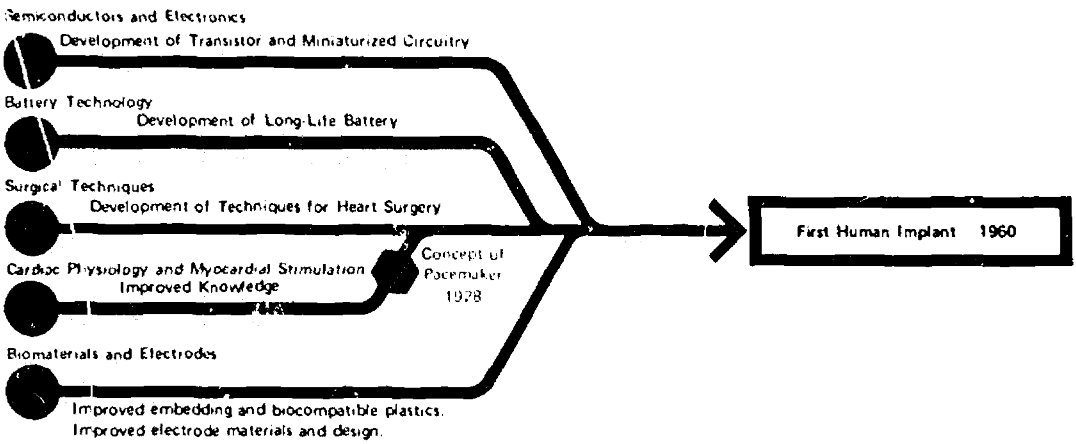
The Heart Pacemaker

The totally implanted cardiac pacemaker is used for treatment of patients with heart-block disorders. The device is an electronic pulser, complete with pertinent electronic circuitry, battery power source, and electrode system, encapsulated in a biocompatible package. The commercial product represents a remarkable example of the confluence of several sciences and technologies upon which its success depends. Included are low-power miniature electronics, sealed long-life batteries, surgical techniques, biomaterials, and cardiac physiology.

Some precursor events occurred well before the 20th century. For example, in the field of cardiac physiology, electrical stimulation of muscle was first observed by Galvani, in 1790. The symptoms of the primary disorder treatable with the pacemaker (now known as the Stokes-Adams syndrome) were described in 1824. Electrical stimulation of the heart was proposed in 1862. In 1886, the term "heart block" was introduced to describe blockage of the synchronous rhythmic contraction of the chambers of the heart. The conduction tissue (the "bundle of His") that transmits the synchronizing impulse between chambers was described in 1893.

Other work, particularly on intracardiac therapy and on surgical techniques, continued through the 1920's, but the first conception of the idea of periodic electrical stimulation of the heart was propounded in 1928 by A. S. Hyman, director of the Witkin Foundation for the Study and Prevention of Heart Disease. In 1930, he applied for a patent on a pacemaker, which incorporated a spring-driven magnetogenerator and needle electrodes, and began to use it successfully, although the spring power limited the useful time period. He failed to gain widespread medical and social acceptance, however, and was even subjected to (unsuccessful) law suits for malpractice. Unable for some time to find a manufacturer to improve and miniaturize his device, he finally reached an agreement with Siemens of Germany, only to have this agreement, and his pacemaker studies, disrupted by World War II. Hyman never returned to work on pacemakers, lacking confidence in his ability to exploit the extraordinary advances in electronics made during the war years. These advances, however, directed toward miniaturization and low power requirements, were to provide the basis for future success in pacemaker technology.

The transistor, the foundation of the new electronics technology, was invented in 1948. Advances in miniaturization and in pulse circuitry came rapidly, utilizing efficiently the low power needs of transistors. Another product of the war effort was a sealed primary battery, the zinc-mercuric oxide alkaline cell, with long life at low current drains. Meanwhile, other contributions to the implantable pacemaker — epoxy for "potting" the electronic components, and biocompatible silicone rubber encapsulation material for long-term implantation — came



from the polymer field. Further efforts included a search for electrode materials and systems free from problems of increasing electrode threshold (minimum voltage needed for consistent stimulation) and insulation leakage in contact with body fluids.

Progress toward the goal of the innovation also depended upon advances in surgical techniques. Procedures were developed, for example, for either insertion of the electrodes through a vein into contact with the inner wall or their direct attachment to the heart muscle, and for implantation of the pacemaker device. The extensive work leading to open-heart surgery, and the complications which occasionally arise (in the form of temporary heart block due to surgical trauma) led to the development of temporary pacing techniques. Open-heart surgery received considerable publicity, and the corresponding dramatic successes had a strong influence on widespread acceptance of this technique and, therefore, on the use of stimulating electrodes in control of temporary heart block. Certain religious and moral questions concerning the inviolability of the heart were sufficiently resolved to permit use of the pacemaker.

Successful clinical application of an external pacemaker for treatment of complete heart block was announced in 1952. With further improvements and external, rather than needle, electrodes, longer term use (up to one week) was reported. However, the technique required high voltage for external pacing, with attendant pain of muscular contraction and possible burns; consequently, interest refocused on direct-stimulation techniques for long-term pacing. By 1958, surgically induced heart block was being treated successfully with directly implanted myocardial electrodes and an external transistorized battery-powered pacemaker. Successful clinical application of a pacing technique using a transvenously inserted catheter electrode to contact the inner wall of the heart was announced. The first fully implantable pacemaker was placed in a human in 1959, but its battery pack required periodic recharging, by induction, and the problem of electrode threshold remained unsolved.

At about this time, Wilson Greatbatch, a biomedical engineer, teamed with Dr. William Chardack, a surgeon, to develop a totally implanted, permanent cardiac pacemaker. Greatbatch applied for a patent on his device in the late 1950's, and he and Chardack tested it successfully in animal experiments. Some difficulty was experienced with electrode threshold, but a new stainless steel electrode system minimized the problem. The first human implant was performed in 1960, marking the successful culmination of the innovation. The device performed well and the patient survived for more than 2 years. Units of this type were marketed in 1961 by Medtronics, whose directors were convinced of the potential market. At that time, however, the need was not universally recognized, and the firm suffered heavy financial losses during the first year. Nevertheless, after that critical period, sales mounted rapidly to a net of $30 million in 1971.

The Medtronic device was of the fixed-rate or asynchronous type, with low power requirements and an expected battery life of up to 5 years. Its success has inspired efforts by numerous investigators and manufacturers to improve the device. For example, an improved pacer stimulates the ventricles in response to atrial contraction. Another concept is that of demand pacing, where the pacer is inactive unless triggered into action by a period of abnormally low heart contraction. Berkovitz extended this concept and, in 1971, patented his Bifocal® demand pacemaker, which may stimulate the atria, or both atria and ventricles, in accord with a preset interval. Nuclear batteries have been used as power sources in an implanted pacemaker, and solid-state batteries with projected lifetimes of up to 10 years have been suggested. The coupling of microelectronics to a nuclear power source has been proposed, with the objective of eliminating lead problems by producing a device small enough for total containment within the heart chambers, rather than the body cavity.

The Decisive Events. Of the 102 significant events recorded, the following 13 were considered decisive:

- In 1926 the Witkin Foundation for the Study and Prevention of Heart Disease established a special committee to investigate the problem of intracardiac therapy, initiated the first concentrated attack on the problems of resuscitation, and, with A. S. Hyman as Foundation Director, provided the base for evolution of his pacemaker concept.
- L. Cordorelli's 1928 report, that the heart beat could be sustained by mechanical stimulation, i.e., thumping the chest, strengthened Hyman's concept of electrical stimulation.
- Hyman's patent application, in 1930, described the first electrical instrument suitable for clinical use in resuscitation.
- Hyman's 1932 publication of his pacemaker experiments caused considerable polarization among advocates and opponents of its use.
- The sealed mercury battery, developed by S. Ruben in 1947, marked the first power source with properties of long life, no gas evolution, and flat discharge characteristics suitable for powering implanted transistorized devices.
- The invention of the transistor by J. Bardeen and W. H. Brattain, in 1948, paved the way for development of miniaturized electronic equipment with low power requirements at low voltages suitable for battery operation.
- The first Biomedical Engineering Group, established by W. Greatbatch in 1952, stimulated interaction of the medical and engineering professions, and was later the source of the association of the two principals jointly involved in developing and implanting the first pacemaker unit.
- The clinical demonstration of external pacing for heart block, by P. M. Zoll, 1952, led to widespread use of electrical stimulation.
- The development of medical-grade silicones by Dow Corning in 1953 provided the necessary biocompatible encapsulating material.
- In 1955, Lillehei used external pacing to combat heart block resulting from cardiac surgery; he later developed a technique for direct attachment of electrodes to the heart wall.
- Weirich and his associates in 1957, treated A-V block with external pacer and electrodes *directly inserted into the heart muscle.* A transistorized, battery - powered external pacemaker was later developed by Bakken for their use.
- Hunter and Roth, in 1959, developed a stable electrode system for the implantable pacemaker, which eliminated problems of electrode degradation in service in the body fluid.
- Chardack and Greatbatch, in 1960, developed the first totally implantable heart pacemaker and implanted it successfully into a human patient. This unit was marketed immediately, and the innovative process was completed.

Implications of the Case. A unique feature of this case history is the long time span, 32 years, from concept to first realization, the longest span among the cases studied. The delay caused by World War II and the inhibiting effects of sociomedical rejection of cardiac manipulation do not account for the entire period. Although Hyman clearly recognized the need and knew what he wanted, certain technologies, such as electronics, batteries, and polymers, had not been developed sufficiently. As the needed technologies reached a level of maturity adequate to support the innovative process, their convergence made it possible to develop and market the device in a relatively short time.

Although this innovation was need oriented, the need was not universally recognized until the late 1950's. The long perseverance of the inventor in the face of social resistance, legal harassment, and attack by his colleagues, is well documented; he gave up only because the available technology was inadequate. A. S. Hyman, the inventor, was his own product champion during his time. A second inventor-entrepreneur appeared later. Management decisions were crucial, in the face of adverse market analysis, possible legal ramifications, and inability to obtain product insurance. The initial invention evolved outside the innovative organization. Government financing was of only peripheral significance. Supporting inventions were needed in the course of the innovation. Informal transfer of knowledge played a role.

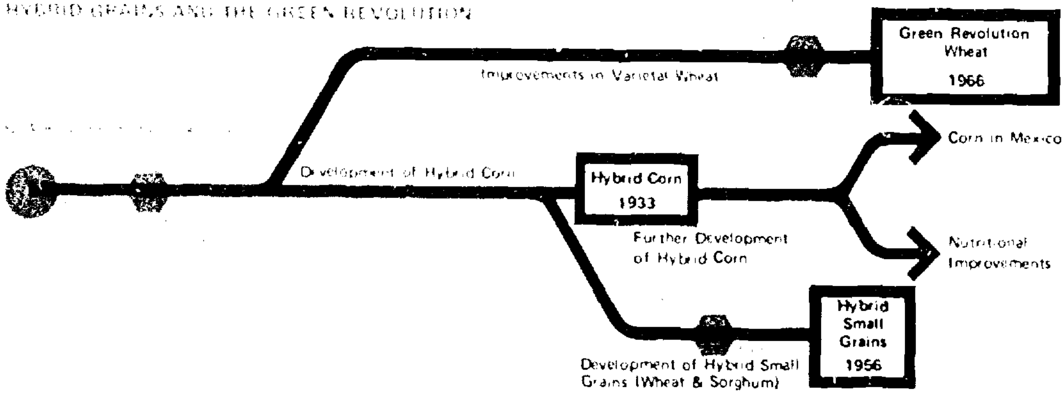
Hybrid Grains and The Green Revolution

This case describes the development of the technology of hybridization and varietal improvement of cereal grains, a technology that led, ultimately, to a world-wide increase in wheat production, a dramatic result aptly termed the "green revolution". In tracing the complex history of this case, it became apparent that more than one innovation was involved. Thus, in order to describe the innovative process consistently and in accord with our stated definition of the term, three unique, but related, major innovations – hybrid corn, hybrid small grains, and the green revolution of wheat – are treated separately.

Hybrid Corn. For hybrid corn, the innovative process begins with the recognition in 1908 of the extraordinary vigor, both in size and growth rate, of first-generation crosses between pure lines. The promise of hybrid corn from inbred crosses was recognized at this date; however, difficulties of seed production made commercialization impractical. The ears of the inbred female parent were small and had few seeds, pollen production was low, and the plants were small, weak, and less drought resistant. Although the first-generation hybrids bore ears with numerous kernels, they could not be used as seed, because the second-generation plants were nonuniform, with loss of vigor. The next major step forward was the development of the double cross in 1918. This technique provided large amounts of seed, but was too complex for the individual farmer and required specialized seed companies. A period of research and development followed, both by the seed industry and by state and Federal agricultural experiment stations.

By 1933 the use of hybrid seed reached the 0.1 percent level for the nation, signifying the start of market acceptance and the culmination of this innovation. Following the drought conditions of 1934 and 1936, during which period

HYBRID GRAINS AND THE GREEN REVOLUTION



the superior hardiness of hybrids was dramatically evident, use of hybrid corn increased rapidly to the level of nearly universal adoption. Research continued, however, and led to the important discovery of cytoplasmic (non-Mendelian) male sterility. By combining the application of this discovery and the associated discovery of means of genetic restoration, hybrid corn could now be grown for seed without the costly and difficult task of hand or mechanical detasseling otherwise required to prevent self-fertilization.

The yield per acre of corn in the United States has increased nearly fourfold since 1935. By 1970, about 80 percent of the hybrid corn was produced by the single-cross system of cytoplasmic male sterility plus genetic restoration, using cytoplasm derived from a single variety. However, in 1970, a new strain of southern leaf blight, particularly virulent in its attack on this type of corn, appeared in the Corn Belt. This new problem, disease susceptibility on a broad front, emphasized an ever-present hazard associated with large-scale use of a single genetic line. Research is continuing into methods of solving this problem.

Hybrid Small Grains. The problem of hybridization of the small grains, such as sorghum and wheat, is much more difficult since their flowers are hermaphroditic. That is, pollen and ovules occur in the same flower. Therefore, hand or mechanical means for control of pollination is eliminated as a practical commercial method. However, the commercial success of hybrid corn and the available genetic knowledge inspired a search for other solutions to this problem. For sorghum, the first conception of a method for hybridization was proposed in 1937. Commercial success was attained by 1956 with the introduction of hybrids using genetic male sterility, thus culminating the innovation. The commercial introduction of hybrids using cytoplasmic male sterility followed in 1957. By 1960, 95 percent of all sorghum in the United States was hybrid.

Although intensive research on wheat has brought forth cytoplasmic male sterile plants, commercial success has not yet been attained. The problem, apparently, is that genetic restoration is incomplete and the hybrids are equivalent only to the best varietals available. On a cost-effectiveness basis, therefore, hybrid wheat is not yet competitive.

Green Revolution Wheats. The Rockefeller Foundation, in 1943, initiated a program to improve agriculture in Mexico. Inasmuch as corn is the staff of life in Mexico, initial efforts were directed toward increasing its yield by hybridization. However, since the subsistence farmer is outside the cash economy and cannot afford to purchase hybrid seed each year, the direction shifted toward other technical and socioeconomic means of improving his lot.

In 1943, wheat yields in Mexico also were low; the soil, the seed, and the agricultural methods were poor; and plant disease was rampant. The Rockefeller Foundation first attacked the stem rust disease problem, by testing hundreds of varieties against various local strains of rust, without success. In 1944, Norman E. Borlaug began crossing to produce improved varieties. The effort was prodigious: of the 66,000 varieties and selections grown by 1951, only four had rust resistance. Even here, the resistance proved insufficient against new strains of the disease. Further development effort culminated in resistant varieties. A parallel effort was mounted to improve the soil. Proper fertilization resulted in up to sixfold increase in yield per acre; however, the plants grew tall and, bending over with a heavy head of grain, created new difficulties with mechanical harvesting. To solve this problem, Borlaug crossed a stiff-stalked dwarf variety into the Mexican wheats, producing a series of semidwarf wheats that responded well to fertilizer. Thus, by 1960, this effort had resulted in a major improvement in Mexican wheat. Meanwhile, another event occurred, without which the development of truly international wheats would have been impossible or seriously delayed. This was the discovery that, beginning in 1950, day-length insensitivity had been accidentally bred into the wheat. This development marked the introduction of the concept of worldwide improvement in production of wheat (and other cereals).

In 1963, experimentation began in India and Pakistan to adapt Mexican wheats to the weather, soil, diseases, and pests of the local areas. High yield varieties were introduced on a large scale in India in 1966, culminating the innovative process. By 1971, nearly 14 million acres, one-third of India's wheat acreage, was in high-yield wheat. From 1964 to 1970, the combination of increased yield and acreage resulted in a dramatic increase of about 85 percent in India's total wheat production. The high-yield wheat varieties, plus fertilizer and pesticides, produced the Green Revolution that drastically reduced problems of hunger and starvation in the world, and converted some grain-importing countries into grain exporters. This exhaustive program and its international benefits to humanity earned Borlaug the Nobel Peace Prize.

The Decisive Events. Fifty-eight significant events were identified for the three innovations in this case. Of these, the following 16 were considered to be decisive.

HYBRID CORN

- G. H. Shull, in 1908, reported hybrid vigor and the development of pure lines in corn, and suggested a method of hybrid corn breeding.
- Independent studies of hybrid corn from crosses between inbreds, by E. M. East in 1908, revealed the potentialities of hybrid vigor for breeding purposes. These two events defined the concept and pointed the way to future breeding methods for commercial development.
- The invention of the double-cross technique, by D. F. Jones in 1918, made possible the commercial exploitation of hybrid vigor.
- The establishment, by F. D. Richey in 1922, of a cooperative program between the USDA and the various Corn Belt experiment stations, provided a major impetus to the development of hybrids suited to local conditions.

HYBRID SMALL GRAINS

- The production of hybrid onions, by H. A. Jones and A. E. Clarke in 1943, using cytoplasmic male sterility, provided the inspiration and direction for similar work in corn, sorghum, and wheat.
- In 1946, R. D. Lewis, at the Texas Agricultural Experiment Station, approved an intensive program to develop hybrid sorghum, which produced commercial seed in 10 years.
- Jones' work, in 1950, on cytoplasmic male sterility with genetic restoration in corn, was important in leading to commercial single-cross hybrid corn and in directing further work on sorghum, wheat, and other cereals.
- Cytoplasmic male sterility in sorghum was found in 1950, by Stephens and Holland. All effort at the Texas Experiment Station was shifted to this approach, culminating in the marketing of hybrid sorghum in 1956.
- In 1951, H. Kihara showed that cytoplasmic male sterility could be bred into wheat. This directed attention to the possible development of commercial hybrid wheat.
- By 1961, J. A. Wilson and W. M. Ross had produced cytoplasmic male sterility in wheat.
- In 1962, J. W. Schmidt, V. A. Johnson, and S. S. Maan found restorer genes for wheat. This discovery, plus that of cytoplasmic male sterility by Wilson and Ross, pointed to the technical feasibility of commercialization of hybrid wheat.

GREEN REVOLUTION WHEATS

- The establishment of the Rockefeller Foundation program in Mexico was significant in that a systems approach to agriculture was applied; this approach provided a favorable environment for N. E. Borlaug's comprehensive program on wheat.
- The introduction of dwarf wheat genes into U.S. wheats, by O. A. Vogel in 1949, led to short-stalked varieties with good fertilizer response. Borlaug obtained the dwarf material from Vogel, for use in developing the high-yielding Mexican wheats.
- Borlaug's breeding of day-length insensitivity into the Mexican wheats, in 1950, was a decisive contribution to the development of international wheats.
- The establishment of the International

Corn and Wheat Improvement Center (CIMMYT) by the Rockefeller and Ford Foundations, in 1963, marked the internationalization of the initially Mexican program, and the beginning of the introduction of Mexican wheats into India and Pakistan.

- By 1966, large-scale importation and planting of the international high-yield wheats took place in India, and culminated in the "green revolution" of wheat.

Implications of the Case. This case is unique in that three major innovations were identified. The three innovations were strongly interlinked, however, through direct interplay of technical knowledge. The historical record is highlighted throughout by the interweaving of Government and institutional funding, and by the influence of federal policy, effective management decisions, and long association of key personnel. An invisible college, need for supporting innovations, and even a serendipitous discovery played a role.

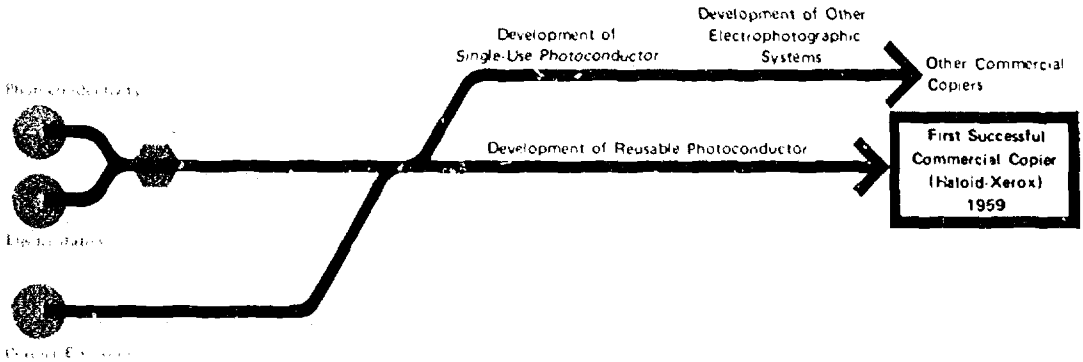
The innovation of hybrid corn was distinguished by the initial recognition of the technical feasibility of hybrid vigor, followed by an early recognition of its value in improving corn production. The initial invention originated outside the marketing organization. There was strong evidence of the importance of the product champion and of direct transfer of knowledge between scientists. The hybrid small grain development was need oriented, with the initial concept originating outside the seed-producing company. The international wheat program was also in response to a need, but the concept developed within the innovative organization.

Electrophotography

Electrophotography is traced from its conception in 1937, through its extensive development period, to the production and marketing of a practical high-speed copier — exactly the kind of machine envisioned by the inventor. Two general methods in use today account for most of the market. One employs a reuseable photoconductor and delivers copy on plain paper; the other uses a paper sheet coated with a photoconductor (e.g., zinc oxide) in a resin binder and delivers the coated paper as the final copy. Now other methods of electrophotography are reaching the marketplace, or are expected soon. In this study the emphasis was on the plain-paper copier, since its development from concept to culmination as a marketed product presents the course of the innovative process in accord with the stated definition of innovation.

In 1935, Chester F. Carlson, a patent attorney, recognized the need for an office copier that would eliminate typing carbon copies or preparing stencils or masters for the duplicating processes. Concluding that a photographic process was indicated, since the only common property of the various originals to be copied would be their light reflectivity, he began his search for technical solutions via the interaction of light with matter. In 1937, he read a report of a unique process of facsimile transmission that dispensed with chemically treated paper. In this process, a pencil of ions was used to produce an electrostatic image in a scanning pattern on an insulating surface. The electrostatic image was then developed by dusting with a fine powder. Strongly influenced by this disclosure, Carlson conceived of using ions to precharge a layer of photoconductive material, the electrical characteristics of which would be those of an insulator in the dark, but which would conduct and dissipate the charge in the exposed areas of the image. Powder dusting would be employed to develop the image. Carlson immediately filed a patent application, and then attempted to develop a working demonstration of the concept, but, working alone, was unsuccessful. In the fall of 1938 he brought in a physicist, O. Kornei, to assist him, and they succeeded shortly in producing the first crude demonstration of electrophotography. Their process consisted of charging sulfur or anthracene plates by rubbing, and dusting with dyed insulating powder to develop the image. The image powder was transferred to waxed paper and fixed by heating.

Following several years of frustrating and unsuccessful attempts to interest a number of companies in taking over the invention, Carlson was able to generate enthusiasm for the concept at Battelle Memorial Institute. In 1944 Battelle



agreed to undertake research to improve the invention and to promote its development. Concerted effort by the team assigned to the project resulted in several improvements and inventions that refined the concept, demonstrated its technical feasibility, and left no doubt that it was ready for the final (and costly) product development and engineering stage of the innovative process. These improvements were: (1) the discovery of the superior properties of amorphous selenium as the photoconductor for this process; (2) the use of controlled corona discharge to provide uniform, fast charging of the photoconductor surface ; (3) the invention of the process of electrostatic transfer of the powder image from the photoconductor to the paper sheet; and (4) the invention of the two-component developer in which the pigment particles are carried by electrostatic attachment to large, heavy carrier particles. When dusted over the suitably charged photoconductor, the pigment particles of the two-component developer are transferred to the charged image areas, and the uncharged background areas are scoured and maintained clean of stray pigment powder by the large carrier particles.

Electrophotography reached the attention of the Haloid Company* in 1945, generating considerable management interest in its potential as a product addition to the company's line. In 1947 a licensing agreement was negotiated by which Haloid supported the research at Battelle, with emphasis on commercialization. In 1950, Haloid produced and marketed its first copier, a slow, manually operated device that did not gain acceptance in the marketplace. Under the direction of J. C. Wilson, the product champion, development and engineering groups at Haloid were charged with the task of solving the many problems to be faced in reaching the goal of a sequentially programmed, fully automatic copier. In 1959-1960 this difficult and complex effort culminated in the production and marketing of the first commercial machine, the Xerox 914 Copier.

Stimulated by the public announcement of electrophotography in 1948, many organizations began studies leading to the second major method, which employs a one-time-use coated paper with a composite layer of photoconductive powder in a resin binder to record the electrostatic image. In 1954 G. J. Young and H. G. Greig at RCA announced the use of zinc oxide as the photoconductive material in such a composite layer. Considerable effort has been expended in basic and applied studies of the properties of zinc oxide and other photoconductors and methods of improving sensitivity, spectral range, and other properties. Electrophotography began to follow a second commercial path employing the one-time-use zinc oxide coated paper; RCA called it Electrofax. A number of companies, under license to RCA and Xerox, have marketed copiers based on the coated-paper principle, beginning with Apeco, in 1961.

The early work with anthracene, the first organic photoconductor to be applied to electrophotography, prompted a search for other

*Later Haloid-Xerox, then Xerox Corporation.

organic photoconductive materials. A number of materials have been proposed, but the requirements are severe: for once-used plates, the material must be relatively low in cost; for reuseable plates, the problem of the softness and low strength of most organics must be surmounted. Photoconductive polymers appear to offer the most promise, particularly those with additives to increase sensitivity. In 1970, IBM introduced a plain-paper copier, employing a reuseable organic photoconductor. The problem of wear is solved by placing the photoconductor on a web that, advanced on demand, presents a new surface as needed to pres^^ve the quality of the copy.

The past decade has seen a rapid diffusion of the technology. Several copiers, both plain-paper and coated-paper types, have appeared on the market here, in Europe, and in Japan. Some innovative modifications have already been developed, and other novel processes are in progress. A greater variety of machines may be expected in the future.

The **Decisive Events**. Of the 66 significant events identified, the following 14 were considered to be decisive in the innovative process:

- P. Selenyi, in 1935, described a facsimile recorder in which the scanned pattern of the electrical signal is stored on an electrostatically charged insulating surface and developed by powder dusting. This precursor event strongly influenced Carlson's thinking and led directly to his conception of electrophotography.
- C. F. Carlson's invention of electrophotography in 1937, involving the novel concept of light-image storage on an electrostatically charged photoconductor, was a major breakthrough.
- The first reduction to practice of the invention, by Carlson and Kornei in 1938, demonstrated the technical feasibility and potential of the process.
- The Battelle agreement with Carlson in 1944 opened the way for the development effort leading to the successful completion of the major inventions needed in support of the innovation.
- In 1945 E. N. Wise invented two-component powder development, which resulted in a major improvement in background cleanliness and print quality.
- W. E. Bixby, in 1946, discovered the superior photoconductive properties of amorphous selenium for electrophotography.
- In 1946 R. M. Schaffert invented the process of electrostatic transfer of the image powder from the reuseable photoconductor surface to the paper.
- In 1946 J. J. Rheinfrank used a fine wire stretched across and above the photoconductor surface, to replace needle-point corona charging. The essentially uniform corona along the wire considerably improved the uniformity of charge on the photoconductor surface.
- In 1947 L. E. Walkup improved the wire corona discharge by using a wire grid inserted between the high-voltage wire and the photoconductor surface. Application of electrical bias to the grid permitted close control of the magnitude of corona-deposited charge on the photoconductor surface, avoiding excessive voltages and the possibility of electrical breakdown of the photoconductor.
- The license agreement between Haloid and Battelle in 1947 marked the first of very important management decisions that committed Haloid to large financial risks and drastically influenced the course of the innovation.
- In 1954 Haloid introduced the first rotary xerographic machine, that is, with the reuseable photoconductor surface on a rotating cylinder. Although not a document copier, this machine demonstrated the rotary-drum principle of succeeding automatic copiers.
- C. J. Young and H. G. Greig disclosed the RCA zinc oxide-resin binder coated-paper electrophotographic process in 1954. The coated-paper process, with a once-used photoconductor surface, is the basis of an entire family of copiers.
- In 1959-1960 the introduction of the Xerox 914 office copier marked the culmination of the innovation and the proliferation of a type of product having a major impact on society and its functions.
- In 1970 IBM introduced a copier with a

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reuseable organic photoconductor coated on a web wrapped around a drum, and designed so that the web can be advanced to replace a worn surface. This event appears to have initiated a new class of machines.

Implications of the Case. Among the internal and external factors having an impact on the innovative process, the inventor's recognition of the need is clearly and explicitly evident. This study illustrates the difficulties of an independent inventor in selling his idea to organizations that might be expected to recognize its potential worth. The influence of both the technological gatekeeper and the product champion is apparent in two separate time periods. The study demonstrates the importance of institutional factors such as management decisions in the face of adverse market analysis, the heavy investment required for the production-engineering phase of the innovative process, and the value of a team effort in problem solving and in producing the supplementary inventions needed to support the original idea. Partial Government support of a special development effort at a crucial period provided needed incentives. This study also illustrates the effects of an unplanned confluence of technology, and the importance of informal transfer of knowledge.

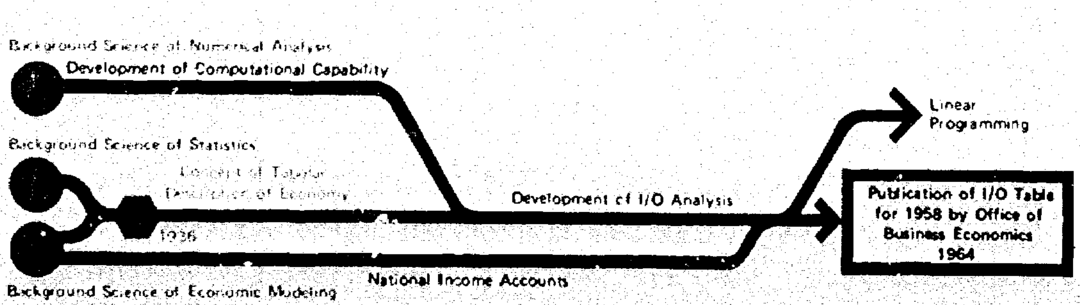
Input-Output Economic Analysis

Input-Output (I/O) Economic Analysis differs from the other innovations in that it is an analytical tool to explain inter-industry economic relationships, rather than an innovation leading to a saleable product. It views the whole economy of a region or country as a single system, in which the information is reduced to an I/O table — a matrix of inter-industry transactions of raw materials, goods, and services, received and delivered among the various producing sectors of the economy. Thus, for example, the effect of changes in demand for the products of any one industry on all other industries may be computed.

The clearly defined concept, as formulated by Wassily Leontief, was outlined in his trail-blazing 1936 paper. The immediate precursor events were difficult to trace, even through Leontief, and it must be concluded that the development originated in the broad background of general economic modeling and statistical analysis. The major aspects of economic theory leading to the formulation of his model include: (a) the tableau format for representing inputs and outputs of the economy, dating back to Francois Quesnay (1758), (b) general equilibrium analysis of Leon Walras (1874), using fixed coefficients of production and representation of the analysis in the form of simultaneous linear equations, (c) the method of balances used for resource allocation decisions by the Soviet government, and (d) the development of national policy analysis, a technique for assessing national economic priorities that provided the motivational basis for I/O analysis. The 1936 paper, failed, however, to attract widespread attention.

Leontief's research led to the 1941 publication of his first book on I/O analysis. Including the inter-industry matrices of the U.S. economy for the years 1919 and 1929, the book provided insight into cause-and-effect relationships among input, output, prices, and consumption patterns between the two years. Publication of the 1941

INPUT-OUTPUT ECONOMIC ANALYSIS



book led directly to Leontief's association with the forthcoming government efforts.

In the same year, in the midst of economic expansion due to mobilization for World War II, Congress expressed concern lest postwar demobilization force a depression and requested the Bureau of Labor Statistics (BLS) to study the economic effects of demobilization. BLS contracted with Leontief at Harvard University to direct production of an I/O table for 1939 for use in predicting the effects of demobilization in the United States. This table also served as a pattern for estimating an I/O matrix for Germany, which, in turn, provided an overview of the German economy that helped the U.S. Air Force select bombing targets. The 1939 table, published in 1945, was also used to forecast steel capacity needed in the postwar year 1947. The resulting prediction – a significant increase – was not universally accepted but later proved correct.

In order to obtain an I/O matrix describing the military economy, the U.S. Air Force supported BLS, from 1948 to 1954, in a major effort, called Project SCOOP. This project yielded an extensive I/O table for 1947. Many nonmilitary applications resulted from the 1947 table, in addition to development of the Emergency and (unfinished) Mobilization Models for the Air Force. In 1953, with a change in administration of the Executive Branch of the Government, Project SCOOP was officially terminated, although some effort continued on an informal basis for a few years.

Project SCOOP was one of the sponsors of the first UNIVAC computer and the sole sponsor of the SEAC computer. Without large computers, the 1947 table (and of course all future I/O work) could not have been constructed. Other contributions to model theory and development, as well as to matrix mathematics and linear programming, were made under Project SCOOP.

Interest in I/O work revived under a broad study (1956-1957) of the national economic accounts, made by the National Accounts Review Committee (NARC). The National Bureau of Economic Research (NBER) organized NARC at the request of the Bureau of the Budget. The NARC expressed concern that foreign governments were outstripping the U.S. in the use of I/O for national-income accounting, and recommended resumption of I/O analysis by the Federal Government as part of its national accounts. The new program was placed in the Office of Business Economics (OBE) of the Department of Commerce in order to integrate all national-account activities in a single system. In 1964, the OBE published a detailed I/O table, using 1958 Census data. This was the first U.S. table integrated with national accounts.

The 1958 table represents the culmination of the innovative process because it marks the end of the experimental period of I/O history. Succeeding tables are regularly prepared by the Federal Government. As this innovation diffused into other applications, it generated supplemental methods of data treatment and analysis.

The Decisive Events. Of the 48 significant events identified, the following 9 were considered decisive:

- Leontief's definitive book of 1941 presented the concepts of I/O analysis and an interindustry matrix model. This book was instrumental in developing large-scale support of I/O research.
- In response to a 1941 Congressional request for a study of the economic effects of demobilization, BLS contracted with Leontief to produce at Harvard an I/O table for 1939. The objective of this contract was to estimate the effects of demobilization on employment. This was the first direct U.S. Government involvement in I/O analysis.
- In 1943, BLS favorably reviewed the Harvard work, and in spite of its deficiencies at the time, recommended continuation at BLS.
- The first large-scale digital computer, developed at Harvard in 1944 by H. Aiken, was used by Leontief to solve the 1939 I/O matrix. This work and later tables could not have been processed without the aid of large computers.
- The 1945 publication by BLS of an I/O matrix for 1939 marked the first such matrix to be published by a U.S. Government agency. Recognition of its potential application to military planning-programming problems led the Air Force to organize project SCOOP.

- In 1948, Project SCOOP was organized to produce an I/O matrix for 1947. This project represented the first multimillion-dollar inter-agency effort in military planning and programming.
- The UN-sponsored First International Conference on Input-Output Economics, in 1952, crystallized world-wide interest in I/O analysis.
- The NARC report to Congress in 1957 was a broad study of national income accounts. It marked a milestone in I/O history by publicizing its value to the economy, and led to the authorization of the 1958 table.
- The 1964 publication of the I/O matrix for 1958 was the culmination of the innovation.

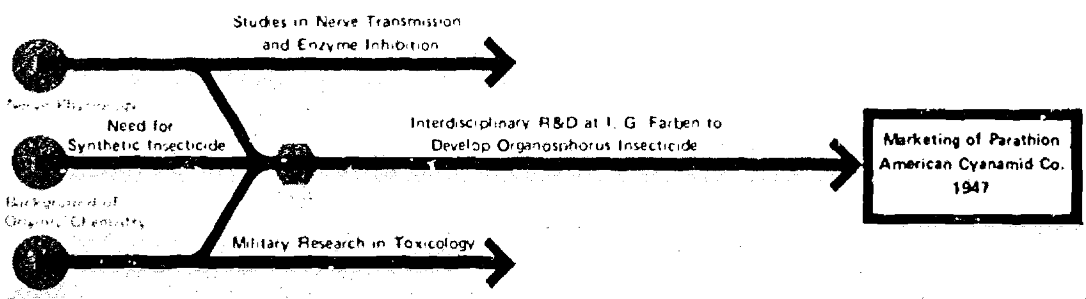
Implications of the Case. This innovation and its applications are intimately associated with Government policy, planning, and funding, and therefore have been affected by these external factors to a degree not noted in the other cases studied. The innovation is an analytical tool, rather than a product; however, we do find a champion; in fact, this role is played by more than one person. The roles of the technological gatekeeper and the invisible college are in strong evidence. Management decisions were important factors at various stages of the innovative process. In fact, a period of "management conservatism" resulted in a temporary shutdown of the process in the U.S. government. There is little doubt that the innovator, Leontief, recognized the need for the innovation. Leontief served also as an independent inventor, outside the organization which completed the innovative process. A confluence of technology occurred in the timely development of large-scale computers, without which the extensive computation needed for the production of I/O matrices could not have been handled. Informal transfer of knowledge and the need for supportive inventions were important factors in the innovation.

Organophosphorus Insecticides

This case describes the development of organophosphorus insecticides to control insect predators -- an indispensable task if the food needs of the world are to be met and the depredations of insect carriers of disease are to be eliminated. The stable broad-spectrum chemicals, such as DDT and other chlorinated hydrocarbons, have performed this task efficiently, economically, and with dramatic benefits to mankind. However, unexpected problems have accompanied their extended use. In part, these problems are associated with the toxicity of such chemicals to man, but of greater concern is their persistence in the environment, and the resultant ecological danger of widespread toxic buildup in higher animals. Another problem is the ability of insects to develop resistance to insecticides to which they were initially susceptible -- a continuing challenge to technological progress.

The first successful approach to the solution of these problems derived from the discovery of the specific properties of the organophosphorus compounds, of which a number are commercially important insecticides. Some are systemic insecticides -- they are absorbed by the plant, which then becomes lethal to insects feeding upon it. Many organophosphorus compounds are relatively nontoxic to mammals and

ORGANOPHOSPHORUS INSECTICIDES



nonpersistent in the environment, and there is considerable potential for finding highly selective variants. Analysis of the innovative process of developing these insecticides has provided insight into the probable directions of future growth and the diversity of chemical means for insect predator control with minimal environmental hazard.

The discovery, by Lange and Kreuger in 1932, of the toxicity of organophosphorus esters containing fluorine, and the recognition of their potential as insecticides, marked the starting point for the subsequent concerted research effort on these compounds. However, their findings did not evoke immediate response within the technical community, and these authors did not pursue the subject. First conception of the technical opportunity was formulated in 1934 by the management of I. G. Farbenindustrie, in recognition of the need for an insecticide to replace the toxic but flammable gases then in use as fumigants. Furthermore, as an economic measure, the German government had curtailed the importation of crop-protecting substances, chiefly rotenone and nicotine, and thereby created an incentive for the production of synthetic substitutes. Gerhard Schrader was appointed to initiate this research.

Schrader began his studies by synthesizing organic compounds in which fluorine alone was introduced. The management of I. G. Farben established a team consisting of the chemist Schrader, a biologist to do insecticidal testing, and a pharmacologist for toxicity studies. The properties of the fluorine compounds were only moderately attractive, and in 1936 Schrader turned to the synthesis of compounds with phosphorus as the central atom.

There followed a long sequence of synthesis and testing of organophosphorus compounds in the I. G. Farben laboratories. More than 2000 compounds were said to have been prepared before the end of World War II. When the war began in 1939, the German work was classified. Of the many compounds prepared, Dimefox exhibited systemic characteristics — on absorption by the plant from the soil (sprayed with an aqueous solution of the compound), the leaves become poisonous to insects. A related compound, Schradan, prepared in 1942, proved to be fairly stable in the presence of lime, a property then considered important, because field applications of synthetic insecticides sometimes included additions of lime. The compound Bladan was prepared in 1939. Only moderately toxic to higher animals, it is as effective as nicotine against aphids; however, it is not stable in the presence of lime.

None of the compounds prepared were effective against the Colorado potato beetle. An infestation of this insect in Germany in 1944, and a shortage of arsenate of lime to combat it, compounded the danger of an acute food shortage and led to an intensified search by Schrader for a suitable material. He shortly found two compounds, Paraoxon and Parathion, effective against the potato beetle and proposed their application without mixture with arsenate of lime. Parathion is effective against a wide variety of insects and has a short residual action. However, it is extremely toxic to humans and must be handled with great care.

Parathion was unknown to the Allies at the end of the war. Its existence was revealed in 1945 in the British Intelligence Objectives Subcommittee (B.I.O.S.) reports of interviews with Schrader. Parathion was first marketed in the United States by the American Cyanamid Company, in 1947. This event is taken to mark the culmination of the innovative process for this case — the production of the first commercial insecticide of this type.

Beginning in 1935, the German government required that new toxic compounds be reported for screening, and the most toxic were classified. Two compounds, initially prepared by Schrader in 1937 and submitted for testing, proved to be extremely toxic. Given the code names Tabun and Sarin, these were selected for manufacture by the German Ministry of Defense.

Interest in the toxicological properties of the organophosphorus compounds spread rapidly beyond the German laboratories. The British Ministry of Supply launched an investigation, in 1939, of the physiological properties of the compounds reported in Germany in 1932. Later the Medical Division of the U.S. Army began intensive studies of toxicity and therapy at Edgewood Arsenal.

It became clear that the toxicological effect of the organophosphorus compounds is pro-

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duced by their irreversible inhibition of the activity of the enzyme acetylcholinesterase, which occurs in nerve tissue in both insects and higher animals. Deactivation of this enzyme results in complete destruction of nerve impulse transmission and disruption of normal nerve functioning. Release of the early information on the insecticides and later the "nerve gases", as they are called, has stimulated intensive research, basic and applied, in several disciplines related to enzyme kinetics and nerve transmission.

In the early 1930's, Dow Chemical Company developed independently a general interest in the properties of phosphorus compounds, including their insecticidal properties. The research program involved synthesis and screening for toxicity and insect lethality. Their work was extended to a search for animal systemics — compounds which, when ingested by animals, afford protection against insect attack. The effort was successful and led to the marketing of Ronnel and Ruelene, the first of a family of animal systemics available from various manufacturers.

Other chemical companies in the United States and elsewhere became interested in synthetic insecticides, some before the end of the war, but the release of the B.I.O.S. reports created more intensive and widespread interest. A large number of compounds have been patented and marketed. Their properties extend over a wide range of specificity, persistence, lethality to insects, and toxicity to mammals. The proliferation of successful products and the needs of mankind have served as impetus to search in new directions for methods of insect predator control, as in the use of techniques involving insect hormones or sex attractants to interfere with the life cycle.

The Decisive Events. Of the 42 significant events identified in this study, the following 10 were considered decisive:

- The management decision by I. G. Farben, in 1934, to embark on a comprehensive program of development of synthetic insecticides assured adequate support, funding, and direction to the new venture, in an area previously unexplored.
- Of parallel importance was the establishment of the I. G. Farben team of chemist, biologist, and toxicologist. This combination of disciplines permitted direct focus on the important aspects of the problem and efficient screening of candidate materials.
- Schrader's decision, in 1935, to investigate fluorine compounds delayed initiation of work on the organophosphorus compounds at least a year. In view of I. G. Farben's knowledge of Lange's earlier work on fluorophosphoric acid esters, it is surprising that Schrader did not turn to these at once.
- The 1937 discovery, by Gross at I. G. Farben, of a relationship between animal toxicity and insect lethality focused attention on this vital criterion for evaluation of all candidate materials. This led to the discovery of the mechanism of toxic action and, in turn, to a rapid extension of basic research on nerve transmission and enzyme inhibition.
- In 1937, Schrader postulated a general structure formula for organophosphorus insecticides, which served as a guide for further studies.
- In 1939 Schrader recognized the need for lime-stable compounds and initiated efforts to produce these.
- In 1941 the discovery by Schrader of plant systemic action marked the beginning of the establishment of an extensive series of products having this desirable characteristic.
- The critical need in Germany, in 1944, for an insecticide to control the potato beetle, was recognized by Schrader. At this time the shortage of arsenate of lime led to an acute problem of food supply.
- Schrader's rapid response was the development of Parathion, a broad-spectrum insecticide effective against the beetle, and the first synthetic compound to reach the marketplace. However, because of the effects of the war, Parathion was marketed first by American Cyanamid.
- In 1951 L. Wade predicted that compounds of the type of organophosphates might be systemically active in animals. This opened up the development of a new class of desirable insecticides.

Implications of the Case. Perhaps the most

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characteristic feature of this innovation is that its success depended upon the full support of management over a 10-year period, the effective work of a competent team, and the dedication of the innovator. Without any of these factors, the project would have bogged down. The social and political pressures upon the organization and the scientific team must have been severe in wartime. The concept was unquestionably need oriented, and the proliferation of products on the market today attests to the success of the innovation, Parathion, in satisfying the need. That the innovation was marketed by a firm not responsible for the original concept was a result of the effects of the war on German industry. Supportive inventions, in the form of a number of new compounds, were required. Government support was provided in Germany. There was an effective interchange and transfer of knowledge among the members of the project team.

Oral Contraceptives*

The development of the oral contraceptive pill began with the formulation of the concept in 1951, and culminated in its commercial production in 1960. The present study identified the decisive events and analyzed their interactions within the innovative process.

This innovation is the control of conception by regulating the release of the egg. Contraception is effected by simulating conditions of pregnancy that are hostile to fertilization. The earliest recorded suggestion of an oral contraceptive was made by Haberlandt in 1921. Having induced temporary sterility by transplanting ovaries of pregnant animals into non-pregnant animals, he speculated that extracts from the ovaries of pregnant animals might be administered as an oral contraceptive. However, the idea was premature. Progress had to await the identification, isolation, and production of the active ingredients in sufficient quantities to permit studies in reproductive physiology.

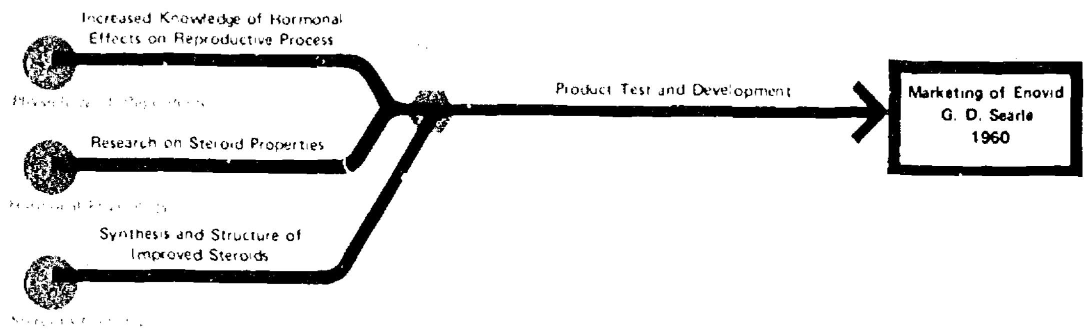
Then in the mid-1930's, prompted by observations of the effect of sex hormones on ovulation, Kurzrok refined Haberlandt's suggestion by specifying an ovulation-inhibiting hormone as the regulator. The idea was still not technically feasible, for an orally active progestin – a hormone producing the physiological conditions of pregnancy – was not yet available. Meanwhile, considerable effort was directed to the synthesis of steroids – the class of chemical compounds which include hormones with the desired properties.

Finally, in 1945, a concept of contraception, approaching the method finally adopted, was proposed by Albright. It involved hormonal prevention of ovulation, plus separate hormonal control of the menstrual period. The available hormones were considered either dangerous or ineffective, and no immediate action was taken.

By 1940, the first of a series of highly important events occurred – the discovery by R. E. Marker that diosgenin, a botanical raw material, could be converted to biologically significant steroids. Aware of the isolation of diosgenin from the root of a native yam by Japanese workers, and recognizing the possibility that a readily available plant source would free the steroid chemist from dependence on animal organs, Marker began an intensive search of the United States and Mexico for an abundant source of diosgenin. Collecting over 400 species of botanicals, his search was rewarded by discovering such a source in a Mexican yam, a plant easily collected without need for explicit cultivation.

In 1944 Marker organized Syntex, S.A. in Mexico to produce steroids from diosgenin. Hormone production by Syntex increased steadily from laboratory to tonnage levels, with a corresponding reduction of price. The large-scale market demand for steroids in the early 1950's was for the production of cortisone, particularly for treatment of rheumatoid arthritis. Considerable progress was being made in steroid synthesis and in preparation of structural modifications exhibiting other biological effectiveness, including increased progestational activity. The research effort included not only an international academic community, but the research teams established at Syntex and in other pharmaceutical houses. Two steroid

*Extension of earlier study in TRACES - NSF-C535 (1968). In order to provide a historical basis for our analysis of the decisive events, it was necessary, in this and the succeeding two case studies, to make full use of the historical data available from the TRACES project.



analogues, norethisterone and norethynodrel, each exhibiting high progestational activity when administered orally, emerged from the laboratories of Syntex and G. D. Searle in time to enter the innovative process.

In this case of innovation, the initial impetus for a safe, sure, and easily administered contraceptive method resulted from the concern of Margaret Sanger of the Planned Parenthood Federation and the philanthropist Mrs. Stanley McCormick over the potential danger of excessive growth of the world population. Early in 1951 they requested a proposal for a research program on contraceptive methods from Dr. Gregory Pincus, of the Worcester Foundation for Experimental Biology. His response was a proposal to develop an oral contraceptive pill that would suppress ovulation. He had a clear vision of the potential effectiveness of such an approach to contraception, the probability of high social acceptance of the method of application, and the potential benefits to mankind.

With his proposal accepted by Mrs. McCormick and funding assured, Pincus became a highly motivated product champion, generating enthusiasm for the program among his colleagues and providing direction for a concerted attack.

The approach was not straightforward, for the progress of steroid chemistry had not yet reached a level that would provide the ultimate materials. Initial animal and clinical studies of progesterone, an ovulation inhibitor readily prepared from diosgenin, confirmed its limited activity for oral use and led to a search for better materials. By 1953, the search was rewarded by the submission of norethisterone by Syntex and the chemically similar compound norethynodrel by Searle. In small-scale tests on volunteers, the products were rated superior progestational agents, both in safety and efficacy. A large-scale evaluation was now necessary, and Puerto Rico was chosen as the site of the experiment. Searle's management, overcoming the traditional position of an ethical pharmaceutical house that drugs are only for cure of disease, and the fear of possible social stigma attached to the term contraceptive, co-sponsored the Puerto Rican trials with the Planned Parenthood Federation. The trials were outstandingly successful; they paved the way for FDA approval of Enovid (Searle's trade name for norethynodrel) for treatment of menstrual disorders in 1957, and for use as an oral contraceptive in 1959. Enovid reached the marketplace as an oral contraceptive in 1960, marking the culmination of the innovative process. Syntex's analogous drug also received FDA approval for menstrual disorders in 1957, and was marketed by Parke-Davis under the trade name Norlutin, but its approval for oral contraceptive use was delayed until 1962 (because Parke-Davis would not enter the oral contraceptive market in 1957). Syntex had to find another licensee, the Ortho division of Johnson and Johnson, who marketed the product under the trade name Ortho-Novum.

Since the introduction of Enovid, extensive efforts have been made to improve the efficacy and safety, and to reduce the cost of this and numerous competitive products.

The Decisive Events. Of the 75 significant events identified in this historical study, 15 were considered to be decisive in the innovative process, as follows:

- The isolation and structure elucidation of the hormone progesterone, by A. Butenandt and others, in 1934, precipitated a race to obtain the pure material for studies of the physiology of reproduction.
- By 1937, the ability of steroidal hormones to inhibit ovulation had been demonstrated by several workers. The low activity of orally administered progesterone was recognized, stimulating an intensive search for an orally active progestin.
- H. H. Inhoffen synthesized ethisterone, the first orally active progestin, in 1938, by a chemical conversion route later used successfully by Searle and Syntex in synthesis of their highly active compounds.
- R. E. Marker's discovery (1941) of the chemical process for converting the steroid base, diosgenin, into progesterone, stimulated his search for an abundant plant source.
- The organization of Syntex, in 1944, marking the introduction of an abundant and cheap source of steroids and starting materials for steroid analogues, stimulated research on chemical derivatives, many of which ultimately reached the marketplace.
- In 1944, M. Ehrenstein and W. M. Allen demonstrated the progestin activity of 19-norprogesterone, a structural modification which became the prototype for future compounds, including the Syntex and Searle products of the innovation.
- In 1944, A. J. Birch developed a simplified synthesis of 19-nor steroids which provided impetus and direction to the steroid chemists involved in the innovative process.
- In 1951, C. Djerassi of Syntex synthesized norethisterone, one of the two compounds used in most oral contraceptive products.
- In 1951, F. B. Colton of Searle synthesized norethynodrel, thus sharing honors with Djerassi.
- The request for a proposal on contraceptive methods, by Mrs. Stanley McCormick and Margaret Sanger in 1951, provided the incentive to G. Pincus and the Worcester Foundation to plan a concerted effort.
- The proposal by Pincus in 1951, and its funding, initiated an integrated program to develop an oral contraceptive. As product champion, Pincus led and encouraged his colleagues to surmount the difficulties in the way of success.
- In 1953, M. C. Chang evaluated the two 19-nor steroids received from Searle and Syntex, respectively, and proved their efficacy and safety on animals; this was confirmed by J. Rock, from clinical tests on a small group of women.
- In 1954, Pincus offered the concept of cyclic control, wherein the drug is withdrawn for a few days to permit a normal menstrual cycle. Avoidance of the physiological and psychological symptoms associated with failure to menstruate undoubtedly influenced the rapid adoption of the product.
- The decision by Searle, in 1954, to press the developmental effort to commercialize the oral contraceptive, was an event requiring considerable courage in the face of possible societal rejection. Syntex was not yet in a position to initiate commercialization at this time, and the full-scale testing needed for FDA approval would have been delayed for a considerable time.
- Searle introduced Enovid as an FDA-approved oral contraceptive in 1960. The marketing of this product marked the culmination of the innovative process.

Implications of the Case. This innovation was need oriented; in fact, it was in direct response to the need expressed by the project sponsor. This account also provides dramatic examples of untimely prior concept, when the state of the art was still inadequate to supply the necessary technology. The importance of the product champion is again evident in this account. Management decisions in the face of possible societal rejection were crucial here. In this case, the initial invention was conceived outside the innovative organization, and supportive inventions were needed. Government financing was not involved. The effects of an invisible college and of personal transfer of knowledge, as well as the unplanned confluence of technology, were also important within the innovative process.

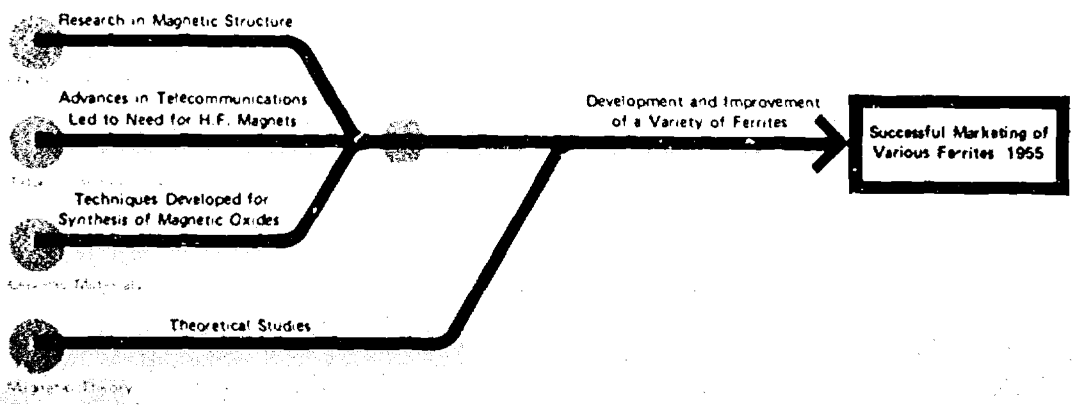
One of the striking features of this case is the complex, truly international interplay of the channels of development — steroid chemistry and physiology. The joint contributions of the academic community and industry, and the role of serendipity were also significant factors.

This innovation involves the production and application of magnetic ferrites, a broad class of ceramic materials that combine the magnetic properties of certain metals with the electrical properties of insulating materials. Some compositions are "hard" or permanent magnets and, as such, find application as replacement for more costly alloy magnets. Others are magnetically "soft", or nonretentive, and are used, for example, to replace iron cores of inductors; here, the inherent high resistance of the material prevents alternating current power losses in the core due to eddy currents. With composition tailored to fit the desired properties, soft ferrites find many other important applications such as in communications, microwave technology, and computers.

The initial concept took shape in the Philips Research Laboratories, Netherlands, in the early 1930's, in response to the need for improved magnetic materials for use in their telephone communications business. By 1933, J. L. Snoek, at Philips, had recognized the potential of magnetic materials exhibiting low electrical losses and the possibility of tailoring chemical compositions to application, and had begun a systematic study of ferrites. Progress was undoubtedly affected during the war years, but by 1946, the importance of compositional homogeneity and correct oxygen content was firmly established, and in 1947 Philips Laboratories reported experimental applications of ferrites to radio and telephone communications, in the form of transformer cores, inductors, and band-pass filters. By 1949, television applications in horizontal-sweep and high-voltage transformers, deflection yokes, tuning slugs, and magnetic shields, as well as loop antennas for broadcast-band receivers, were reported. By 1952, the 100 tons of ferrite per month used in the communications and television industries indicated widespread market acceptance of this product.

An important extension of the applications of ferrites into the microwave region of electromagnetic wave phenomena resulted from wartime needs associated with military communications and radar technologies. Many of these applications were based on the theoretical behavior of a microwave gyrator, a circuit component whose properties had been described in principle several years before. Following the war, many laboratories, including Bell Telephone Laboratories (BTL), developed increased interest in magnetic phenomena and in applications in the microwave region. Meanwhile, ferrite compositions to meet the requirements for microwave applications were being developed by E. Albers-Schoenberg at General

*This case was adapted from the TRACES project.



Ceramics. In 1951, C. L. Hogan of BTL recognized the characteristics of ferrites that satisfied the requirements for a microwave gyrator, and in effect, reduced the concept to practice. By 1955, the invention had been extended to several microwave applications in circuit elements, such as phase shifters, delay lines, isolators, and circulators.

Following World War II, another class of ferrites, termed square-loop ferrites in reference to their unique response to an external magnetic field, evolved from military needs for more computer power. An Air Force project at Harvard and an Office of Naval Research (ONR) contract with MIT resulted in developing the concept of a static magnetic storage element for use in a digital computer memory. The storage principle is based on the switching properties of the square-loop ferrite core, the magnetic polarization of which depends upon the previously applied magnetic force. Thus each ferrite core is a binary-logic storage element, switchable by the magnetic field associated with suitable current pulses. In 1948, General Ceramics assigned Albers-Schoenberg the task of developing square-loop ferrites. In 1952, he filed the first patent on square-loop ferrite compositions. Further work at General Ceramics and at MIT led to ferrite core compositions with improved properties, including faster switching times. Magnetic core memories are key components of present-day high-speed computers.

Hard ferrites – permanent magnet materials – were developed in the Philips laboratories in the late 1940's to mid-1950's. Their extensive applications in the military and consumer market range from the cores of permanent-magnet motors to the small magnetic plaques for cupboard-door and shower-curtain retention.

Therefore, by 1955, suitable formulations had been developed and were accepted in the marketplace, for each of the major applications of ferrites, thus marking the culmination of the innovation.

The Decisive Events. Of the 65 significant events recorded in this case study, the following 7 were identified as decisive:

- In 1933, J. L. Snoek began to work at Philips on magnetic materials, with emphasis on the relation between composition and electrical-magnetic properties. Clearly, the funding of this research was indicative of management's recognition of the growing need for such materials in the telecommunications industry. Snoek served as product champion through the early development period.
- The post-World War II establishment of research-funding agencies of the Federal government, starting with the Office of Naval Research in 1946, allowed significant funding of academic and industry research teams in pursuing programs whose results would serve the national interest. The funding of Project Whirlwind at MIT for the development of larger, faster computers is an example that markedly affected the future technology of ferrites.
- The increased emphasis on magnetic research at Bell Telephone Laboratories in the late 1940's was a consequence of management's recognition of the need to extend the applicability of ferrites into the higher frequency regions to meet the communications problems of the future.
- The decision, by General Ceramics in 1948, to bring Albers-Schoenberg from Germany to pursue a ferrite program, marked the beginning of a rapid development of ferrite technology in this company. Albers-Schoenberg, because of his dedication and his ability to obtain funds from the Signal Corps and from Project Whirlwind, was able to serve as product champion of the program, which ultimately led to the marketing of square-loop and microwave ferrite devices.
- Went and Van Oosterhart reported on the magnetically hard properties of barium ferrite, in 1949. Philips' recognition of its economic potential led to the commercial development of this important class of materials.
- In the period of the late 1940's to the early 1950's, realization developed widely that soft ferrites were generally useful in the electronics industry, and led to the initiation of considerable applications research, some with Government funding. The result was the widespread proliferation of applications

as electronic components.

- The invention of the microwave gyrator by C. L. Hogan, in 1951, was a direct outcome of microwave research funding by BTL that permitted the establishment of a team of experts, but was based on the previous theoretical description of the gyrator and on background research in gyromagnetic phenomena.

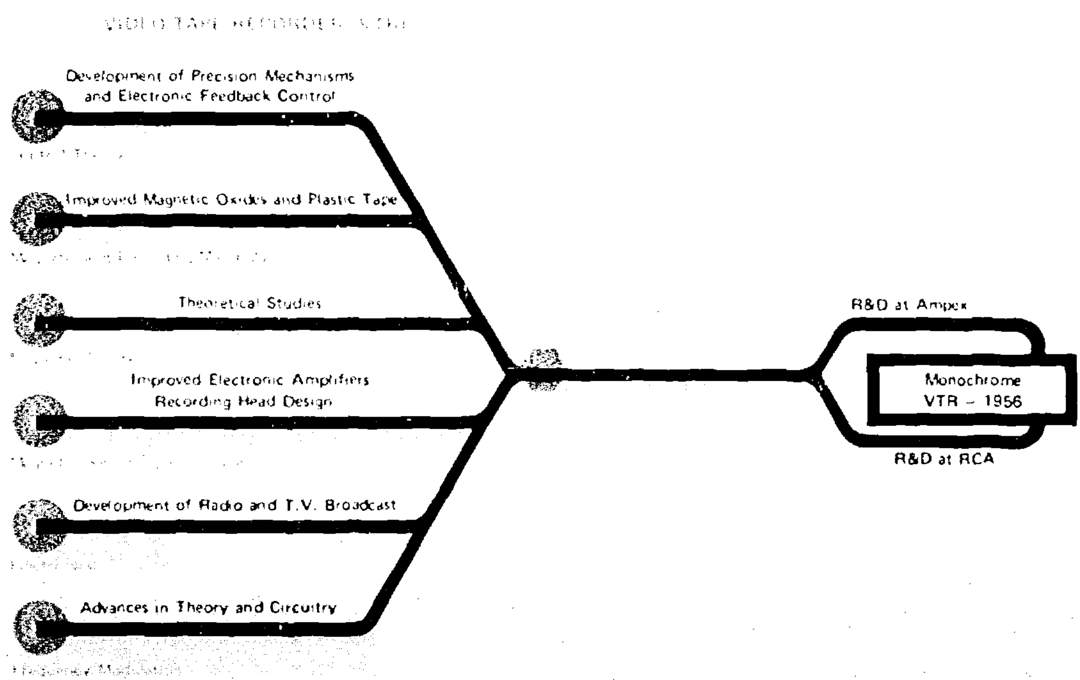
Implications of the Case. For each class of ferrite – hard, soft, microwave, and square-loop – discussed in this account, the need was clearly recognized and the potential market could be visualized. Management decisions were highly important; they represented major financial and technical commitments. The product champion was evident at least twice. The innovation was the outcome of a confluence of basic science and technology along several channels of development. This account demonstrates the value of the team effort within the innovating organization. Government funding played a major role in some phases of this innovation. Supportive inventions were required. There was considerable personal interchange of technical knowledge in the later stages of the innovative process.

Video Tape Recorder*

This is an account of the development of the video tape recorder (VTR), an instrument that caused a revolutionary change in the operation and programming of the television-broadcast industry. At first conception of the innovation, in 1950, the need for a technique to record video signals for subsequent rebroadcasting was universally recognized. It would not only solve the time-zone problem in network programming, but also provide greater programming flexibility for the individual station.

The technical situation, however, was far from satisfactory. The requirements for quality video recording were unequivocal; to record the amount of information in a video signal requires a bandwidth (frequency range) of recording frequencies extending over 4 million hertz (cycles per second) versus a typical bandwidth, for high-fidelity audio recording, of 15,000 hertz. Simply to extend existing audio techniques would require unrealistic tape speeds of 1500 inches per second (over a mile per minute), and correspondingly unrealistic quantities of tape and size of reel per hour of broadcast

*This case was adapted from the TRACES project.



time. Direct-recording techniques did not appear feasible, unless supported by some unanticipated breakthrough.

In 1950, Marvin Camras of the Armour Research Foundation suggested a solution to the tape-speed problem – rotating the tape recorder head relative to the moving tape. The management of the Ampex Corporation, a licensee of Armour and a recognized manufacturer of quality broadcast audio recording equipment, considered the VTR an obvious,and needed extension of its product line. In 1951, the decision was made to develop a VTR following the rotating-head concept. C. P. Ginsburg, hired by Ampex as project manager early in 1952, identified the four major technical problems to be solved:

- Rotating heads of adequate precision, with appropriate tape transport.
- Servo techniques to control head-to-tape positioning.
- Servo system for reel-to-reel tape positioning.
- Carrier modulation with sideband width comparable to the video signal bandwidth.

On Ginsburg's project team was a young technician, R. M. Dolby, who rapidly solved the problem of servo techniques for precise tape positioning. Within 10 months, the first crude model of a rotating head tape-transport system had been developed, and progress appeared to be satisfactory. However, the project was terminated officially for a year because of internal conflict; nevertheless, Ginsburg continued his work after hours until the project was renewed. The rotating head was now a sophisticated precision device, with four heads set in a high-speed rotating cylinder, against which a 2-inch wide magnetic tape was rapidly drawn parallel to the axis of the head. Thus the magnetized track was a succession of transverse helical segments. The problem of synchronizing the signal from one segment to the next was also solved.

Certainly the most serious problem was that of the frequency limitations of direct tape recording, which, in the period of the innovation, was about 100 kilohertz. For recording color video signals, a bandwidth of 4.5 megahertz is required; thus direct recording is impossible. The solution is to modulate a carrier wave with the desired signal. Amplitude modulation, as used in commercial radio broadcasting, was tried first, without success. Then a frequency modulation (FM) technique, using a carrier frequency slightly higher than the desired signal bandwidth, was proposed. Although FM radio transmission was well known at the time, conventional practice would require a carrier frequency of at least 40 megahertz. The decision of the Ampex team to try their FM scheme was bold, but the results were completely satisfactory and justified the gamble. It turned out that theoretical support of the narrow-band FM concept had already been published, but this information was not known to the Ampex team at the time. The conceptual system was now reduced to practice, but several engineering and production problems had yet to be eliminated. The decision was made to develop monochrome VTR first; this reduced the bandwidth requirements from 4.5 to 2.5 megahertz and simplified the production problems to be met.

Meanwhile, a market study had been made for the Ampex Board of Directors. The report was unfavorable, but Ginsburg persuaded management to continue. In 1956, the project was publicly demonstrated at the annual meeting of the National Association of Radio and Television Broadcasters (NARTB). During the first day of the demonstration, Ampex booked sales of nearly $5 million of monochrome VTR machines, then equivalent to nearly 30 percent of the company's annual business, thus bringing the innovation to its culmination.

Unknown to the two contenders, the VTR development was actually a race between Ampex and RCA. Ruling out the rotating head as impractical, RCA took two approaches in the early 1950's: direct recording and multiple-channel recording. The direct-recording approach was soon recognized as impractical, and major emphasis turned to a multiplexing technique in which the recorded video signal was divided into 10 channels, each carrying a portion of the band of frequencies. FM recording was also ruled out as impractical, and a further constraint was imposed – that color transmission be recorded. Nevertheless, considerable progress had been made when Ampex announced its monochrome VTR. RCA reorganized its development approach along the lines of Ampex, but added color capability, and entered into a cross-licensing agreement with Ampex. Thus a significant contribution was provided to Ampex's later development of its color-recording capability.

The Decisive Events. Of the 77 significant events identified, 5 were considered to be decisive, as follows:

- The inauguration of regular TV broadcasting by the BBC, in 1936, marked the beginning of this vast industry. Without the potential demand for a VTR by this industry, it is unlikely that the innovation would have been developed.
- The rotating-head concept of Camras was unique and highly innovative. Without it, the project would not have progressed far, but the concept posed difficult problems of head design and of track positioning and synchronization.
- The decision of a small company like Ampex to embark on an ambitious program of this type was courageous, even though it was based on recognition of the potential soundness of Camras' concept and on the company's considerable experience in the recording industry.
- The successful development of servo techniques and tape-head synchronization by Dolby was crucial to the overall innovation.
- The successful incorporation of FM recording into the VTR system completed the development of the concept into a full reduction to practice, and provided management impetus to proceed with engineering, production, and marketing plans.

Implications of the Case. This account is highlighted by recognition of the specific need by the management of Ampex and by the dedication of the product champion and his research team. Based on the Camras concept (innovation conceived outside the company) and the company's internal expertise in the recording field, the final product emerged in only 6 years. This does not imply that the ambience of science and technology made no contribution; the historical account traces the background through several channels of development such as electronics, radio and television broadcasting, magnetic theory, magnetic recording materials, and magnetic recording systems. In the absence of this entire historical background, the Camras concept would have been meaningless. No outside assistance of Government funding was involved in this case. The innovation, causing a "revolution" within the TV industry, promoted changes in the nature and frequency of broadcasts of mobile transmissions, such as news and sports events, and in the use of instant replay, time-zone planning, editing, and program storage. An unfavorable market analysis failed to halt the effort; the product champion prevailed. Supportive inventions were needed. As entrepreneur, Ginsburg contributed to the innovative process not only his personal drive and guidance, but a high order of managerial insight and direction regarding Dolby's work that maximized the latter's contributions to the project.